AN INVESTIGATION OF METHODS FOR REDUCING THE USE OF NON-RENEWABLE ENERGY RESOURCES FOR HOUSING IN THAILAND

A Dissertation

by

SAKKARA RASISUTTHA

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

DOCTOR OF PHILOSOPHY

May 2005

Major Subject: Architecture

AN INVESTIGATION OF METHODS FOR REDUCING THE USE OF NON-RENEWABLE ENERGY RESOURCES FOR HOUSING IN THAILAND

A Dissertation

by

SAKKARA RASISUTTHA

Submitted to Texas A&M University
in partial fulfillment of the requirements
for the degree of

DOCTOR OF PHILOSOPHY

Approved as to style and content by:

Jeff S. Haberl (Chair of Committee)	Larry O. Degelman (Member)
David E. Claridge (Member)	Valerian Miranda (Member)
Phillip J. Tabb (Head of Department)	

May 2005

Major Subject: Architecture

ABSTRACT

An Investigation of Methods for Reducing
the Use of Non-renewable Energy Resources for Housing in Thailand.
(May 2005)
Sakkara Rasisuttha, B.Arch., Khon Kaen University, Thailand;
M.Arch., Illinois Institute of Technology, Chicago
Chair of Advisory Committee: Dr. Jeff S. Haberl

The purpose of this research is to develop methods that reduce energy consumption in a residential building in a hot and humid climate region (Thailand) using efficient architectural building components and renewable energy (solar energy) to produce electricity, domestic hot water, and supplemental cooling by night sky radiation.

Improving the architectural building components, including building materials, is an option to reduce energy consumption in a building. Using renewable energy sources is another option to reduce the consumption of non-renewable energy. In residential buildings, solar energy has been utilized for space heating and domestic hot water using active solar collector systems and for generating electricity using photovoltaic (PV) systems. One photovoltaic system, the hybrid photovoltaic-thermal (PV-T) collector system, has been developed by several researchers over the last 20 years. The hybrid photovoltaic-thermal (PV-T) collector system is a combination photovoltaic (for producing electricity) and solar thermal collector (for producing hot water). Theoretical and experimental studies of this collector have highlighted the advantages of the hybrid PV-T collector system over separate systems of PV and solar collector in term of system efficiency and economics. Unfortunately, very little experimental data exists that demonstrates the advantages of a combined system. Therefore, one of the objectives of this study conducted was an experimental study of this system as an auxiliary energy source for a residential building.

Night sky radiation has also been studied as a cooling strategy. However, no attempt so far could be found to integrate it to a hybrid PV-T collector system. The night sky radiation strategy could be operated with the hybrid PV/T collector system by using existing resources that are already present in the solar system. The integration of the night sky radiation into the hybrid PV-T collector system should yield more productivity of the system than the operation of the Hybrid PV-T system alone.

The research methods used in this work included instrumentation of a case-study house in Thailand, an experimental PV-T collector system, and a calibrated building thermal simulation. A typical contemporary Thai residential building was selected as a case-study house. Its energy use and local weather data were measured and analyzed. Published energy use of Thai residential buildings was also analyzed as well to determine average energy consumption. A calibrated computer model of the case-study building was constructed using the DOE-2 program. A field experiment of the thermal PV system was constructed to test its ability to simultaneously produce electricity and hot water in the daytime, and shed heat at night as a cooling strategy (i.e., night sky radiation). The resultant electricity and hot water produced by the hybrid PV-T collector system helped to reduce the use of non-renewable energy. The cooling produced by the night sky radiation also has to potential to reduce the cooling load. The evaluation of the case-study house and results of the field experiment helped to quantify the potential reduction of energy use in Thai residential buildings.

This research provided the following benefits: 1) experimental results of a hybrid PV-T solar collector system that demonstrates its performance compared to typical system of separate photovoltaic and solar collector, 2) results of night sky radiation experiments using a photovoltaic panel as a radiator to demonstrate the performance of this new space cooling strategy, and 3) useful data from the case-study house simulation results and guidelines to assist others in transferring the results to other projects.

DEDICATION

To my father, my mother, and my sister for their love and support.

ACKNOWLEDGMENTS

I would like to express my appreciation to advisory committee. This research would not have been accomplished without their guidance. My sincerest gratitude goes to Dr. Jeff Haberl who guided me with his kindness, dedicated attention, expertise, and knowledge throughout the study period.

My gratitude is given to my mother who always supports me with everything she can help me to finish this dissertation. I felt warm in my heart while she was with me in College Station during the final months this study. I would like to give special thanks to Mr. Jeerasak Muntangkul who is the owner of the case-study house. He was very kind to allow me to use his house as a case-study. I also wish to thank Ms. Wimolkae Wonglasin and my sister, Kritika Rasisuttha, for maintaining the data loggers and sending the data files to me.

I would like to thank Dr. Atch Sreshthaputra for giving me a very useful program, "ATCHWEA", that helped for the preparation of the Bangkok weather file used in this research. I appreciate the help provided by my Thai friends for helping me move the experimental box from the Architecture Woodshop to the solar test bench on the roof of the Langford Architecture Building on the Texas A&M University campus. I would like to thank Mr. Kwanchi Roacha-nakanan for helping me assemble and paint the experimental box. Particular thanks are due to Mr. Charles Tedrick for giving me advice on construction of the experiment box, operating the machines in the woodshop, and safety in the woodshop. I also would like to thank Mr. Kelly Milligan for his advice and help in constructing the many electronic devices used in the experimental box.

TABLE OF CONTENTS

CHAPTER Page

CHAPTER Page

CHAPTER Page

Page

LIST OF FIGURES

Page

Page

Page

Page

Page

Page

Page

LIST OF TABLES

Page

Page

CHAPTER I

INTRODUCTION

1.1 Background

1.1.1 World Environmental Problems, Energy Use, and Trends

The world's primary energy sources consist of fossil fuels such as oil, natural gas and coal. Unfortunately, combustion of fossil fuels releases carbon dioxide (CO_2) and other green-house gases, as well as pollutants that have contributed to environmental problems such as global warming, air and water pollution, and other damage to the earth's ecosystems. Unfortunately, the world's energy consumption continues to increase, which will undoubtedly worsen the environmental problems.

In 2001, the world's energy consumption was 404 quadrillion Btu (1 Quad = 1 x 1015 Btu) and is projected to increase by 58 percent to 640 Quads from 2001 to 2025 (i.e., 1.9 percent average annual growth) according to the Energy Information Administration (EIA, 2003). The United States, the world's leading energy consumer, used about 24 percent (97 Quads) of the world's energy use in 2001 and is projected to increase its energy use by 43 percent to 139 Quads by the year 2025 (i.e. 1.5 percent average annual growth) (EIA, 2003). In developing countries, which are in Asia, the Middle East, Africa, and Central and South America, energy consumption was 139 Quads in 2001 and is expected to increase by 94 percent to 270 Quads over the same period (i.e. 2.8 percent average annual growth) (EIA, 2003). Thus, by 2025, the energy use in the developing countries will constitute about 42 percent of the total global energy consumption.

1.1.2 Thailand's Energy Situation

Thailand's energy consumption decreased at the rate of 8.9 percent during the period of 1997-1998, due to the Asia's economic recession. In 1998, Thailand's total energy consumption was 1.83 Quads, which was consumed by four sectors: transportation – 41.3 percent, industrial – 32.2 percent, residential and commercial – 22.4 percent, and other – 4.1 percent (DEDP, 1998). In spite of the total decrease, energy consumption in the residential and

---

This dissertation follows the format of *ASHRAE Transactions*.

commercial sector increased by 1.6 percent in 1997, while there were drastic reductions in other sectors. Furthermore, electric demand in the residential sector increased by 17 percent from 1996 to 1998 (DEDP, 1998). After Asia's economic crisis, the Thai economy recovered and energy consumption dramatically increased. In 2002, Thailand's total energy consumption was 2.2 Quads (a 20 percent increased from 1.83 Quads in 1998), a relatively high average annual growth rate of 6 percent compared the long term (2002 to 2025) average annual growth rate forecast by the EIA for developing countries in Asia. Finally, Thailand's total electricity consumption increased by 24 percent from 1998 to 2002 (from 79,899 GWh to 99,122 GWh).

Unfortunately, over 80 percent of Thailand's energy comes from non-renewable energy (DEDP, 1998). Furthermore, since Thailand depends on imported energy, which constitutes about 43.4 percent of the total energy consumption, Thailand's energy supply is very dependent on world energy market fluctuations, which will cause havoc with Thailand's economy.

1.1.3 Thai Housing and Energy Efficiency

In 1996, there were 15 million private households in Thailand according to the National Statistical Office (NSO, 1996). Of those, 12 million or 80 percent were single-family detached houses, which comprised about 50 percent of the total residential energy use. The remaining 20 percent of the dwellings (3 million dwellings), which are row houses and apartments, consumed as much energy as the detached housing. Interestingly, most of the Thai row houses are also used for residential and commercial activities such as retail shops, dental clinics, restaurants, or even garages. Therefore, the Thai residential building energy use depends upon the performance of the building's envelope (wall, window, and roof) as well as the energy use of the other activities contained within the residence, such as cooking, lighting, etc.

The typical Thai residential construction is concrete post and beam construction, which has been adopted because of severe termite infestation and limited supplies of wood. In the past, most of the residential building materials were hardwoods, which were abundant in the rainforest of Thailand (FAO, 1981). In the past, hardwoods were used in almost every component of the buildings such as columns, beams, walls, and floors. Today, reinforced concrete is the most common structural material in Thailand's building industry, especially in residential buildings. In residential construction, concrete is not only used to support building structures, it is also used for brick mortar (i.e., cement) and whitewash stucco finishing of the brick and concrete block walls. Concrete and brick are high thermal mass materials, but have

low thermal resistance (R-Value) (approximately 2.0 and 3.3 $h \cdot ft^2 \cdot F/Btu$ respectively) (TGPPC, 1996). These material properties allow heat, which is mainly from the exterior environment such as solar radiation and outside air temperatures, to be stored in the building envelope. In addition, the embodied energy of these materials is high, so it results in high-energy use in the manufacturing and construction phases. Chulsukon (2002) showed that lightweight walls could be substituted for brick walls to provide an improved, sustainable low- energy houses in hot and humid climates. Unfortunately, the typical construction materials used in Thai houses are not energy efficient and need to be improved.

1.1.4 Renewable Energy

Using renewable energy as an energy source is another option to reduce the consumption of non-renewable energy. In residential buildings, solar energy has been utilized for space heating, and domestic hot water, and for generating electricity using photovoltaic (PV) solar systems. Such systems would seem to be ideal for Thailand since Thailand is located near the equator and has high levels of sunshine year-round. Bangkok's monthly average daily radiation on a horizontal surface varies little from January to December (ranging from of 16 to 20 MJ/m^2) (Duffie and Beckman, 1991). Thus, solar energy could be an abundant source of energy for Thailand. Since more than 40 percent of Thailand's energy is imported, and with the awareness of environmental problems, the Thai government has been promoting the use of PV through research funds and through demonstrations of PV systems in residential buildings. Although PV is still new in Thailand's housing industry, with the government's new policy, the potential for PV systems to become an essential key to reducing energy use in Thai residential buildings is promising.

One photovoltaic system, the hybrid photovoltaic-thermal (PV-T) collector system, has been investigated by several researchers over the last 20 years (Rockendorf et al., 1999). The hybrid photovoltaic-thermal (PV-T) collector system is a combination photovoltaic (for producing electricity) and solar thermal collector (for producing hot water) system. Studies of this collector have highlighted the advantages of the hybrid PV-T collector system over separate systems of PV and solar collector in terms of system efficiency and economics. Unfortunately, very little experimental data exists that demonstrates the advantages of a combined system. Therefore, one of the objectives of this study is to conduct an experimental study of this system as an auxiliary energy source for Thai residential building.

1.2 Purpose and Objectives

The purpose of this research is to study methods that will lead to a reduction of energy consumption in a residential building in hot-humid climates using efficient architectural building components and renewable energy systems (solar energy) to produce electricity, domestic hot water, and supplemental cooling.

The research objectives are to:

1. Identify and characterize the energy use of a case-study house in the hot-humid climate of Thailand.
2. Identify energy efficient residential design features for typical houses in a hot-humid climate using a calibrated simulation.
3. Develop and test a hybrid Photovoltaic-Thermal (PV-T^2) system.
4. Apply the test results of the hybrid PV-T^2 system to the case-study house.
5. Develop generalized design and housing characteristics in terms of energy conservation and affordability, which are appropriate for hot-humid climates.

1.3 Organization of the Dissertation

This dissertation is comprised of nine chapters. This chapter discussed the background, purpose, and objectives of the research.

Chapter II reviews and discusses the previous studies that are related to this research. The review of the literature, which provides the basis for conducting this research, includes human thermal comfort, energy efficiency in housing in Thailand, hybrid photovoltaic-thermal solar collector systems, analysis tools for solar collectors and photovoltaic systems, and thermal simulation programs and techniques.

Chapter III discusses the significance and limitations of the research as well as contributions of the research.

Chapter IV discusses the methodology developed for this research. It includes measurements from a case-study house, experiments with a hybrid photovoltaic-thermal system, simulations of the case-study house, which incorporates the PV-T^2 experimental results and an economic analysis.

Results of this research are presented in five chapters (chapters V to IX). Chapter V presents the results of the survey of the case-study house, including the measured thermal conditions of the house, energy use, and an analysis of the measured data, and thermal comfort conditions.

Chapter VI presents the results of the experiments on the hybrid photovoltaic solar heating and radiative cooling (PV-T^2) collector system. Three experiments were performed in this research using the hybrid PV-T^2 collector system, which include experiments to determine the solar thermal collection efficiency, experiments to determine electricity generation efficiency, and experiments to determine night sky heat rejection performance.

Chapter VII presents the results of the simulation of the case-study house, which include the calibration of a DOE-2 model against measured data and utility bills. This chapter also presents the results of the investigation of the energy efficient strategies including thermal and electrical energy produced by the hybrid PV-T collector system used to improve the case-study model.

Chapter VIII presents the results from a life-cycle cost-benefit analysis of the investments and savings on the building energy efficiency strategies including the hybrid PV-T collector system.

Finally, Chapter IX summarizes this research and proposes recommendations for improving residential buildings in hot and humid climates and the future research in this area.

CHAPTER II

LITERATURE REVIEW

This chapter reviews literature that relates to this research. The reviewed literature is categorized into five areas: 1) Human thermal comfort, 2) Energy efficiency and solar energy use in housing in Thailand, 3) Hybrid photovoltaic-thermal (PV-T) solar collector systems and night-sky radiation, 4) Analysis of photovoltaic and solar collector systems, and 5) Thermal simulation techniques for buildings. The first section, thermal comfort, reviews human thermal comfort and studies of thermal comfort in hot-humid climates such as Thailand. The second section reviews the Thai government's energy policy, studies and projects on energy efficient houses, and research into photovoltaic systems for residential buildings in Thailand. The third section reviews hybrid photovoltaic-thermal solar collector systems, which are the systems that this research intends to develop and test, and night-sky radiation, which is a cooling strategy that uses the hybrid PV-T collector as a heat rejecter. The fourth section reviews computer programs that this research used as tools to estimate solar energy collected by the hybrid PV-T solar collector system. The last section reviews building energy simulation programs and the calibration of building simulation models.

2.1 Human Thermal Comfort

The most commonly used definition of human thermal comfort is that by ASHRAE Standard 55-1995, *Thermal Environmental Conditions for Human Occupancy* (ASHRAE, 1995, p.4). However, Thailand's preference for thermal comfort may be slightly different from ASHRAE's. This is evident from two thermal comfort studies that were focused on Thailand's climate. (Busch, 1990; Jitkhajornwanich, 1998).

2.1.1 ASHRAE Thermal Comfort

ASHRAE Standard 55-1995 specifies thermal environments or comfort zones that are acceptable to at least 80 percent of occupants during light, primarily sedentary activities (i.e., resting activities: sleeping, reclining, quiet seated, relaxed standing) (ASHRAE 1992, 1995).

The Standard 55-1995 has divided the human comfort zone into two regions for summer and winter to account for different clothing levels (clothing insulation values or clo values) between seasons. During the summer months, people wear lighter clothes or fabrics than during the winter months. Figure 2.1 shows the ASHRAE Standard 55-1995 human comfort zones.

The boundaries of the winter comfort zone are 64 °F wet bulb for the upper humidity limit, 36 °F dew point temperature for the lower humidity limit, and 68°F and 74°F effective temperature (ET*) lines for the respective lower and upper temperature limits. The boundaries of the summer comfort zone are 68 °F wet bulb for the upper humidity limit, 36 °F dew point temperature for the lower humidity limit, and 73°F and 79°F (ET*) lines for the lower and upper temperature limits respectively.

The lower limit (36 °F dew point) prevents drying of the skin and mucous membranes. However, the upper limit of the comfort zone has been controversial. ASHRAE Standard 55-1995 was revised from ASHRAE Standard 55-1992, which specified 60 percent relative humidity as the upper limits of the summer and winter comfort zones (see Figure 2.2). The upper limit of 60 percent relative humidity was based on the considerations of preventing of mold and mildew growth (Berglund, 1998). This limit was challenged by the evaporative cooler manufactures for not being based on human comfort and also for being too restrictive for the evaporative coolers (Berglund, 1998). Hence, the upper humidity limits were changed to those shown in Figure 2.1

For this research, since thermal comfort is a main concern; ASHRAE Standard 55-1995 will be used to evaluate thermal comfort conditions of the case-study house. However, since humidity control to avoid the growth of microorganisms is significant, the upper limit of 60 percent relative humidity of ASHRAE Standard 55-1992 is also a criterion to evaluate the conditions of the case-study house.

2.1.2 Studies on Thai Thermal Comfort

The two studies reviewed that concerned Thai thermal comfort included Busch (1990) and Jitkhajornwanich (1998). Both of these studies focused on thermal comfort in Bangkok, which is in the tropical Southeast Asia region. The first study (Busch, 1990) investigated the indoor thermal comfort (air conditioned and naturally ventilated) in Thai office

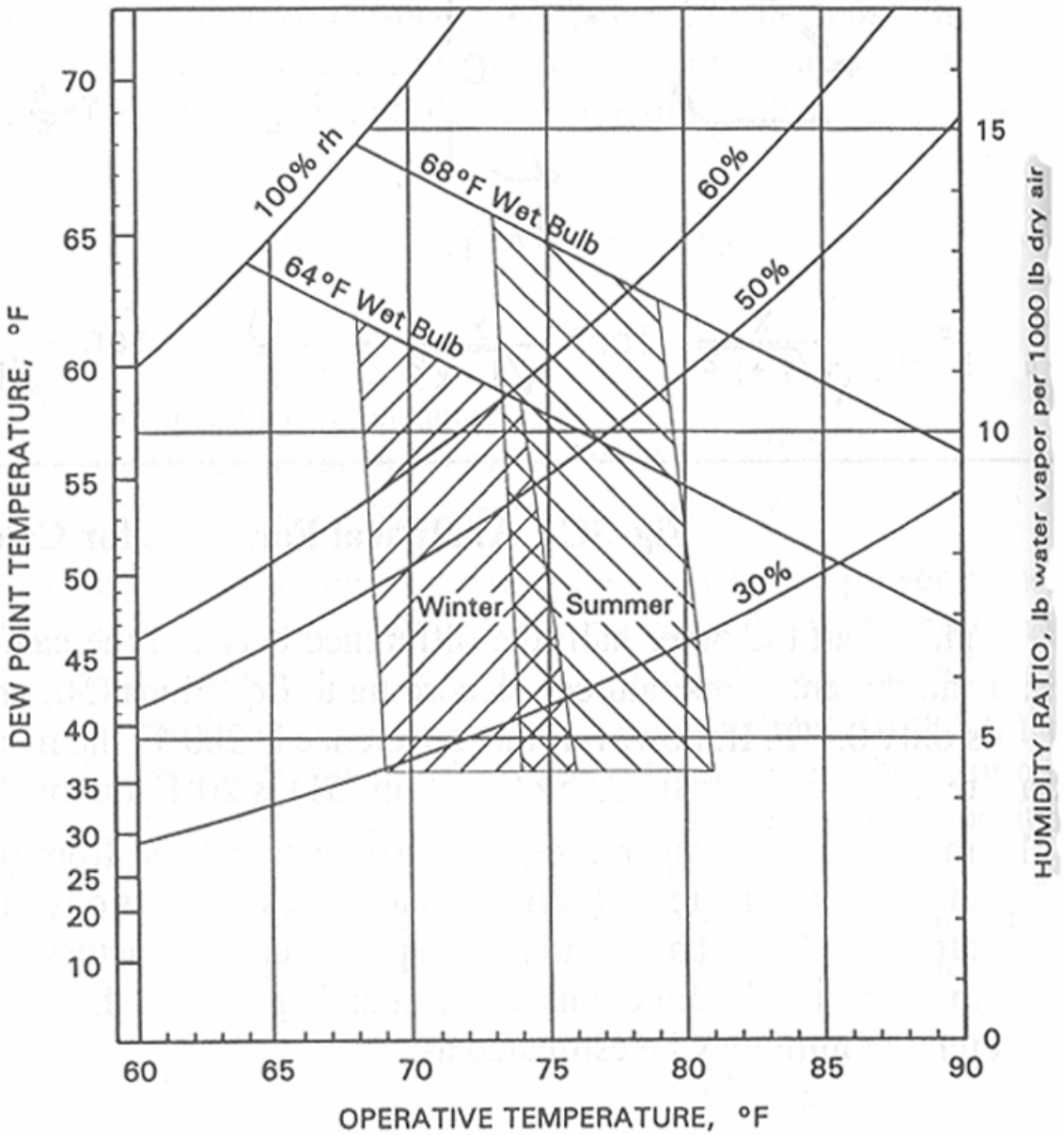


Figure 2.1 *ASHRAE Summer and Winter Comfort Zones: Standard 55a-1995. (Reprinted with permission. 2001 ASHRAE Handbook—Fundamentals. © American Society of Heating, Refrigerating and Air Conditioning Engineers, Inc., www.ashrae.org).*

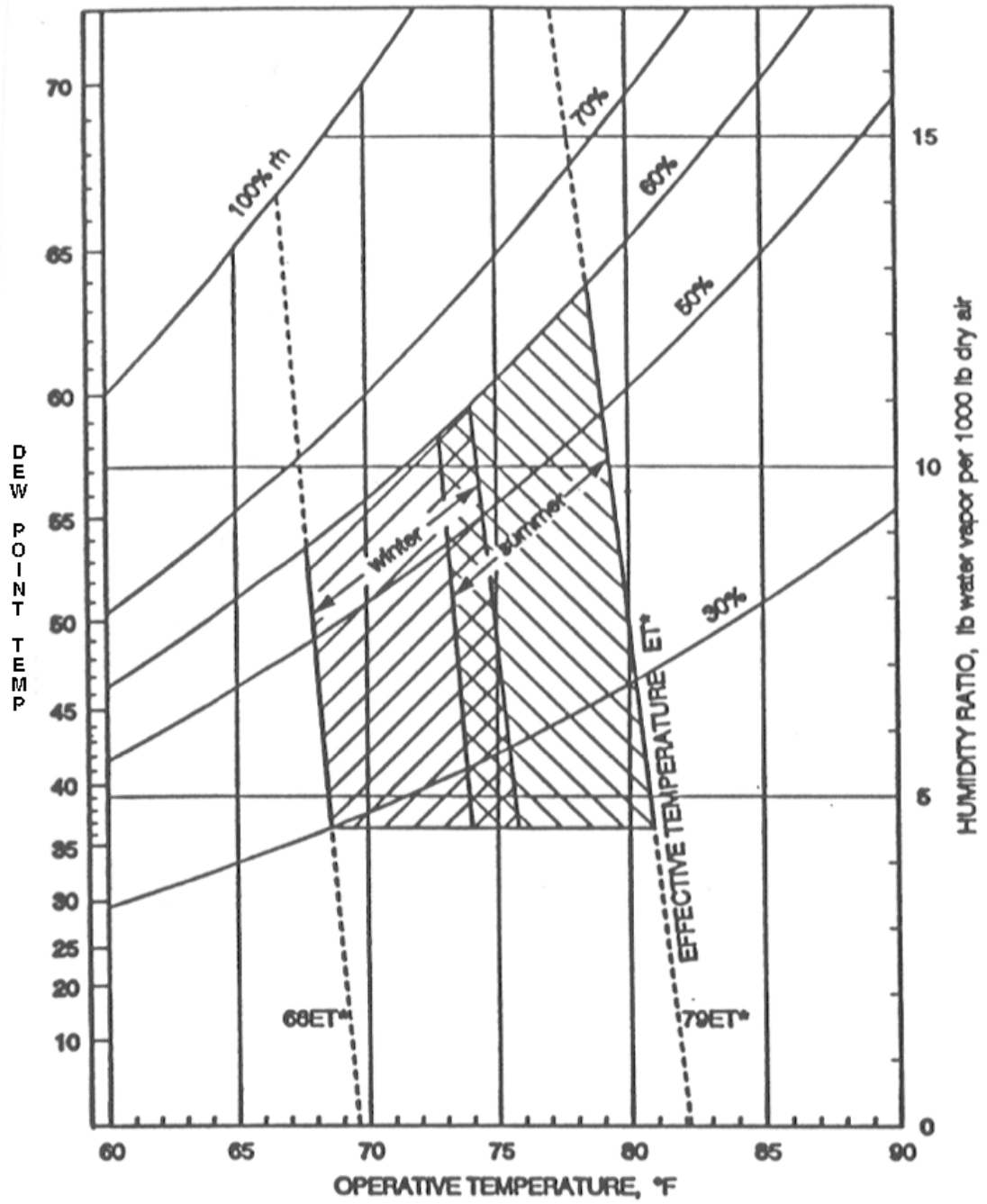


Figure 2.2 *ASHRAE Summer and Winter Comfort Zones: Standard 55-1992. (Reprinted with permission. ASHRAE. 1992. Thermal environmental conditions for human occupancy. Standard 55-1992 © American Society of Heating, Refrigerating and Air Conditioning Engineers, Inc., www.ashrae.org).*

environments. The second study (Jitkhajornwanich, 1998) investigated the thermal comfort in transitional spaces (i.e., entrance halls, lobby areas, foyers) for indoor (air conditioned and naturally ventilated) and outdoor environments.

In Busch's study (1990), air-conditioned offices and naturally-ventilated buildings were studied. More than 1,100 Thai office workers were given a survey questionnaire and physical measurements were taken at their office. For the physical measurements, dry-bulb temperature, relative humidity, globe temperature, and air velocity were measured. The result of the thermal comfort conditions were reported using Effective Temperature (ET*) as a thermal comfort index. The ET* is an environmental index that combines the thermal effects of the four environmental variables (i.e. temperature, radiant temperature, humidity, and air velocity) into a single index (Busch, 1990). ASHRAE (2001, p. 8.6) defines the ET* as "…the temperature at 50 percent relative humidity that yields the same total heat loss from the skin as for the actual environment."

The study showed that the average neutral temperature of Thai office workers was 25.0 °C ET* (77.0 °F), and 25.7 °C ET* (78.3 °F) for the rainy season from May to October. The range of thermal comfort for all cases was from 22 °C ET* (71.6 °F) to 30.5 °C ET* (86.9 °F), which exceeded ASHRAE's summer comfort zone outward by 4 °C (7.2 °F). This analysis of comfort conditions in naturally-ventilated buildings showed that the subjects preferred 27.4 °C ET (81.3 °F), while the subjects in the air-conditioned buildings preferred 24.7 °C ET (76.5 °F) for their neutral temperatures.

The second study (Jitkhajornwanich, 1998) focused on the experience of subjects in transitional spaces of buildings during the cool season of Bangkok from November to January. The research stated the reason for investigating transitional spaces was that "…such spaces are extremely critical in the process of conditioning the response of building users in passing from the exterior to the interior and vice versa. " (Jitkhajornwanich, 1998, p.113). The result showed that the expected and preferred environments and adaptation of respondents determined the actual thermal sensation. The subjects in the transitional spaces preferred 27.1 °C (80.8 °F) for their neutral temperature. The range of thermal comfort was between 25.5 °C (77.9 °F) and 31.5 °C (88.7 °F), which also exceeded ASHRAE's summer comfort zone outward by 5.5 °C (9.9 °F).

From both studies, there was some agreement in the neutral temperature in the natural ventilated building of Busch's study (27.4 °C or 81.3 °F) and the neutral temperature in

Jitkhajornwanich's study (27.1 °C or 80.8 °F). However, the lower limit of the comfort zone of Busch's study (22.0 °C or 71.6 °F) is significantly lower than that of Jitkhajornwanich's study (25.5 °C or 77.9 °F). These studies on thermal comfort in Thailand are very significant to the proposed research. Since one of the proposed objectives is to identify energy efficient residential design features for a typical Thai house. These energy efficient design features must reduce energy use in the building and also condition occupied spaces that need to meet the occupant's thermal comfort. Therefore, this study will also consider that the average Thai's thermal comfort temperature is relatively higher than those specified by ASHRAE.

2.2 Energy Efficiency and Solar Energy Application in Housing in Thailand

2.2.1 Energy Policy

Although Thailand's total energy consumption decreased due to the economic recession of 1997, the energy consumption in the residential and commercial sectors increased despite the recession. The Thai government enacted the Energy Conservation Promotion Act (ECPA) in March 1992. This act aimed to reduce energy consumption in large buildings such as factories and commercial buildings. Unfortunately, energy conservation in the residential sector is not governed by the ECPA. Energy conservation in the residential sector is promoted in other ways such as encouraging citizens to use energy efficient electric appliances, and energy-saving house construction, which are available to the public in the form of pre-drawn houses at a minimum cost (around $1 for a house).

Promoting the use of renewable energy is also one of the strategies to reduce energy consumption in residential buildings. In the 8th National Social and Economic Development Plan (1997-2001), the National Energy Policy Office (NEPO) of Thailand funded research, development and demonstration of photovoltaic technologies such as a pilot project where roof-top, grid-connected photovoltaic systems were installed on houses (Krissanapong, 1997). Major applications of PV systems including water pumping and battery charging systems were built in rural areas. Grid-connected PV systems have also been promoted for houses in urban areas. During 1998-1999, grid-connected PV systems were installed on 10 households in Bangkok through the support of NEPO and the Electricity Generating Authority of Thailand (or

EGAT). The promotion and support of the use of renewable energy such as biomass and PV technologies have been continued in the 9th National Social and Economic Development Plan (2002-2006). This early support of PV by the Thai government has helped expand the use of residential PV systems. According to one study, the annual growth rate of PV demand in South-East Asia countries is expected to 15 % per year, which compares to a 10 % per year increase expected for industrialized countries (Muntasser et al., 2000).

2.2.2 Studies and Projects of Energy Efficiency Houses

The energy-saving house project, as mentioned earlier, was funded by the Energy Conservation Promotion Fund (ECON Fund), which was established under the Energy Conservation Promotion Act (Energy Conservation Promotion Fund, 2000). The project's aim is to design prototypes of energy-saving Thai houses. The prototypes were designed by Plan Architect Limited, Bangkok, Thailand and the Faculty of Engineering at Chulalongkorn University, Thailand. Construction plans of four single-family detached houses and an instruction manual for the homeowner were published in July 2000 (Humanist Co. Ltd., 2000). The energy efficient design features included applying passive cooling strategies such as building orientation, building construction and materials, ventilation opening, shading devices, and vegetation and landscape design. The houses were designed without air conditioning systems. Brief descriptions of how to select efficient appliances and electric devices are also described in the booklet. A significant element that made the energy-saving houses different from typical Thai houses was the use of light-weight concrete blocks in the walls, versus the typical concrete blocks and masonry bricks. Light-weight concrete has a higher heat resistance value (R-value) than typical concrete block and brick, and also has much less embodied energy.

A report about the observed room temperatures in one of the energy-saving houses was presented in the Thai Energy Efficiency Journal (in Thai) (Humanist Co. Ltd., 2000). The analysis showed that the living-dining room temperatures were lower than the outside temperatures in the daytime on the hottest day of the year (in April), and the nighttime room temperatures were about the same as the outside temperatures. The data also showed that the room temperature was in the range of 27.5 °C (81.5 °F) to 32.5 °C (90.5 °F). Unfortunately, this is higher than the Thai neutral comfort temperature for natural ventilated buildings as reported in Busch's study (27.4 °C or 81.3 °F) and Jitkhajornwanich's study (27.1 °C or 80.8

°F). However, only room temperatures of the hottest day of the year were presented (Humanist Co. Ltd., 2000). Humidity is also a factor of human thermal comfort. Therefore, further performance assessment of energy consumption, room temperature and humidity conditions in the energy-saving houses either by simulation or monitoring the real buildings will be needed to assure that the energy-saving houses are suitable for Thai environment.

Another well-documented example of energy conservation in Thai residential buildings is the house of Boonyatikarn (1999). Passive and active design concepts were used in this house to bring indoor air conditions into the comfort zone. Passive design strategies include lowering the house's micro-climate temperature around the house using landscaping, water pools, and natural ventilation. Earth-cooling techniques also helped reduce the cooling load of the air conditioning system on the ground floor. High R-value materials for the building envelope (i.e., wall, window, roof), use of less heat generating devices and efficient appliances in the house were also used. This study showed natural ventilation was able to maintain comfort conditions for 4 months of the year (July to October). An atrium in the house helps ventilate the air during this period of the year as well. In the hottest season, the "keep-the-heat-out" concept is combined with the earth-cooling technique and an air conditioning system. The techniques used to keep the heat out of the interior space of the house include sealing the house from the hot and humid outside air. The concept of the "stack effect" is also used to allow the hotter air in the occupied space rise to the top of the ceiling of the house, where it is exhausted.

The earth-cooling techniques used high heat conducting materials, such as Granite, as the floor material, to help bring the coolness from the earth to the room through the floor. He claims that the floor temperature may be close to 27 °C (80.6 °F), which is about the average of Thailand's earth temperature at the depth of 2 feet (Boonyatikarn, 1999). The air conditioning system also takes advantage of the earth to pre-cool the incoming outside air before it is treated by the air conditioning system. The study suggested the pre-cooled air system may not be cost effective because of the high investment and the limited period of time that the system can work effectively (2-3 hours per day in January and February). For the other cooling periods, two 1.5 ton variable-speed air conditioning units were used. Finally, a heat pipe system was operated with cooling coil of the air conditioning system to help with dehumidification.

The performance of the house included measurement of the energy used by the air conditioning systems during the peak period on the hottest days. His results showed one ton of air conditioning can handle the space up to 110 m^2 (1,184 ft^2). During the off-peak period, one

ton of air conditioning served 220 m^2 (2,368 ft^2) of space. Normally, one ton of air conditioning in the typical Thai house serves only about 20 m^2 (215 ft^2).

The thermal performance of Thai residential buildings was also studied by Parker (1991, 1995). Results show that the reduction of heat transferred through the ceiling in Thai residential buildings is a significant strategy for improving energy efficiency (Parker, 1995). By installation of 7.5 cm (2.95 inches) fiberglass insulation in the ceiling, the size of air conditioning systems could be reduced by about 33% (Parker, 1991). Using more energy efficient air conditioning systems and improving the building's envelope may reduce energy use by the air conditioning systems by over 40% (Parker, 1995).

Although there are only a few of studies on Thai houses that related to energy efficiency, results from the work of Boonyatikarn and Parker show significant improvements in energy efficient Thai houses.

2.2.3 Solar Energy Projects in Thai Residential Buildings

Utilization of a solar energy technology (photovoltaic system) in Thai residential buildings was initiated in 1997 by a grid connected photovoltaic systems pilot project for residential buildings. The main objective of the project was to study the feasibility of utilizing photovoltaic systems in Thai residential buildings. The project was run by Electricity Generating Authority of Thailand (EGAT) and funded by NEPO, which subsidized 45.7 % of the total cost of the project (54.3 % of the cost was provided by the owners of the buildings). Ten photovoltaic systems were installed on ten Thai houses in the Bangkok Metropolitan area. The installation of the systems took about a month and was finished in March of 1998. Eight of the ten photovoltaic systems used single crystal silicon cells, while the other two used amorphous silicon cells. Each of the photovoltaic systems included photovoltaic arrays, a junction box, an inverter, and a power meter.

2.3 Hybrid Photovoltaic -Thermal Solar Collector Systems and Night Sky Radiation

2.3.1 Hybrid Photovoltaic -Thermal Solar Collector Systems

Hybrid PV-T collector systems have been studied for more than 20 years. A number of researchers have presented theoretical as well as experimental studies on the hybrid PV-T collector systems. The reported hybrid PV-T collector systems were designed and constructed differently. However, in general they are basically comprised of a PV panel and a heat transferring system in which air or water is used as a heat transfer medium to remove heat from the PV collector. Studies of this collector have highlighted the advantages of the hybrid PV-T collector system over separate PV or solar thermal systems in terms of PV efficiency and system efficiency. Hybrid PV-T collector systems also have an advantage in residential energy needs, where the area for the installation of PV and solar collectors are limited. In addition, combining the two collector functions reduces overall costs for support structures and installation (Hendrie, 1979).

Imre et al. (1993) reported results of an experiment on a hybrid PV-T collector system that used water as a heat transfer medium. Results showed electricity output increased by about 7 percent at 1000 W/m^2 insolation, because cell-temperature of 60 °C (140 °F) could be reduced to 49 °C (120 °F) by removing the heat from the PV cell. Total maximum effectiveness of the system is over 60 percent.

Garg presented a mathematical model of a hybrid PV-T collector system that uses water as a heat transfer medium (Garg and Agarwal, 1995). The model had the aperture of the collector of 2 m^2 (21.5 ft^2). Results showed that system efficiency is maximized when the flow rate was about 0.03 kg/s (3.97 lb/min or about 0.48 gpm). The model predicted the system performance at about 60-80 percent. Garg also presented a simulation model of a hybrid PV-T system that used air as a heat transfer medium (Garg and Adhikari, 1997; 1999). In their analysis single-pane and double-pane systems were simulated and analyzed. Results show parameters that affect efficiencies of the system were mass flow rate, duct depth, collector length, and solar cell density.

Bergene and LØvvik (1995) also proposed model calculations of a hybrid PV-T system. There model was based on the models for flat-plate solar heat collectors presented by Duffie and Beckman (1991) with modifications due to the addition of the solar cells. The model had a heat absorber attached to the back of solar cell. The heat was then removed by

water through a piping system. A glass cover was also included in the model. The model predicted the performance of the system fairly well with system efficiencies of about 60-80%.

Model calculations of a hybrid PV-T collector system were also presented by Sopian et. al. (1995). Air, as a heat transfer medium, was passed through the hybrid PV-T unit using two configurations; single-pass and double-pass. Their results showed the system efficiency increased as the mass flow rate increased. The results of analysis showed that the double-pass PV-T system yielded better performance than the single-pass PV-T system at a normal operating collector mass flow rate range. The improved performance of the double-pass PV-T system over the single-pass PV-T system was attributed to the beneficial cooling of the PV cells and the reduction in the temperature of the glass cover.

Tripanagnostopoulos et al. (1996) tested a hybrid PV-T system with two additional elements: glazing and a diffuse reflector (a flat aluminum sheet). Their results showed the thermal energy efficiency of water heating was doubled when the additional glazing was added, but PV efficiency was decreased by about 10-20%, compared to the PV efficiency without the heat transfer system. Electrical energy output from the PV panel was increased by integration of the reflector. Thermal energy output was also increased by the reflector. The reflector gave a 20% increase in solar irradiance on the PV surfaces and this in turn increases the electrical energy output. The system was then equipped and tested with both the additional glazing and the reflector. The results showed that the system yielded a higher electrical energy output than the normal PV-T system and thermal energy output was at satisfactory temperature levels.

Experimental work with the Hybrid PV-T collector systems was conducted in the hot climate of Riyadh, Saudi Arabia by Harbi et al. (1998). The system used water as a medium for transferring heat from the PV panels. The results showed that the hybrid PV-T collector system was not suitable for the Riyadh environment, because of very high ambient temperature in the afternoon that decreased the PV module's efficiency (30% below its rated efficiency). However, the high ambient temperatures in the summer yielded a good thermal efficiency of the water heating system.

Recently, an experimental study of a hybrid PV-T collector system was carried out by Huang et al. (2001). The purpose of their study was to compare thermal performance of the hybrid PV-T collector system with a conventional solar thermal collector. The results showed that the efficiency of solar hot water produced by the hybrid PV-T collector system was about 76% of the efficiency of the conventional solar thermal collector.

Hybrid PV-T collector systems have also been studied using simulation. Modeling and simulation of a hybrid PV-T collector system was studied by Kalogirou (2001). A computer program, TRNSYS, which is a transient simulation program and Typical Meteorological Year (TMY) weather conditions for Nicosia, Cyprus, were used to model and simulate components of the system. Photovoltaic panels were attached to a theoretical heat exchanger, through which water was then circulated. The study found that the optimum water flow rate of the 27.4 ft^2 system was about 25 l/h (0.11 gpm). The hybrid PV-T collector system increased the mean annual electrical efficiency of the normal PV system from 2.8% to 7.7%. It was estimated that the system could provide about 50% of the hot water needs of a house.

Small numbers of PV-T systems have been manufactured and custom made for buildings in Europe. Sørensen and Munro (2000) surveyed and reported manufacturers of commercial PV/T collectors and PV-T projects. The survey found 23 PV-T projects or products. However, only four appeared to be commercially available products. Three of the four were water-type, PV-T collectors, which were developed by Chromagaen Solar Energy Systems in Israel (product named "Multi Solar System"), and by SolarWerk and SolarWatt in Germany (product named "Spectrum"). Another was a roof/façade integrated air type PV-T named "PV SolarWall", which was developed by Conserval Engineering Inc. in Canada. The three water-type PV-T collectors were similar, using flat plate solar heat collectors with PV cells integrated on aluminum plate as an absorber. The PV was also glazed on the outer layer of the module. Of those water type systems, only the Chromagaen Solar Energy System's Multi Solar System reported the daily performance, which showed outputs of 1.5 kWh/m^2 heat and 0.4-0.8 kWh/m^2 electricity in Israeli the climate. PV Solarwall, which is an air-type PV-T system, is able to collect thermal energy four to five times larger than PV energy and the overall efficiency is reported as 70 percent (Conserval Engineering, 2003). The PV Solarwall can deliver thermal energy up to 500 W/m^2 for space heating. It was also estimated that the PV Solarwall could reduce the payback time of a typical PV system by a factor of three to four.

Although there have been some PV-T systems commercially available in Israel, Europe and North America (Canada), the PV-T systems are very new to the solar energy community and therefore results have not been standardized. To resolve this problem the International Energy Agency (IEA) established a joint working group (IEA PVPS Task 7 Activity 2.5) to evaluate PV-T systems in 1999. The joint working group consists of two IEA implementing agreements: Solar Heating and Cooling Program (SHCP) and Photovoltaic Power Systems Program (PPSP). The objectives of the joint working group cover aspects of PV-T systems

including design specifications, test methods, performance optimization, and market analysis. So far the tasks of the joint working group have not been finished. However, a road map on PV-T systems was drafted and prepared for the 2nd meeting of the IEA SHCP and PVPS joint working group in June 2000 (Leenders and Sørensen, 2000). The road map defines short, medium and long term objectives and issues that need to be studied on the PV-T systems. A draft plan for organization of the working group, which involved engineers, researchers, industry and end users, was also presented. A new task group to work on the PV-T systems is forming under SHCP since it was realized that the primary theoretical and monitoring part needed expertise of the Solar Thermal community. The task group was expected to run for three years starting in June 2004.

Other issues related to PV-T systems are also being studied by the IEA's task group. Research on PV-T systems using amorphous PV modules as heat absorber of water based PV-T collectors was conducted by collaborative work group of Ecole Polytechnique Federale De Lausanne, Enecolo AG, and Ernst Schweizer AG on behalf of the Swiss Federal Office of Energy (2000). The final report, which is a key reference document for the IEA's task group, was published in June 2000. The study showed that the most important technical aspects of the PV-T module were high solar absorption which the module needs to work at high temperature with low emissivity. In this report, absorption values and emissivity coefficients of PV cells were measured. The research concluded that the photovoltaic (PV) thin film technology was likely to be suited for the application of PV-T systems technically and financially. The a-Si cells seemed to be stable under thermal cycling test; it reported that some tested cells had not changed their original properties at a temperature of 210 °C (410 °F) for 10 hours.

2.3.2 Night-Sky Radiation Cooling Strategies with Hybrid PV-T Systems

Night-sky radiation has been studied theoretically by Martin (1989), and is covered by the classic textbook by Duffie and Beckman (1991). There are also experimental studies or projects that utilize night sky radiation as a cooling strategy, includeing the research by Saitoh and Fujino (2001), and Khedari et al. (2000).

Night-sky radiation cooling was used as a cooling strategy in a study of an advanced energy-efficient house (HERBEMAN house) (Saitho and Fujino, 2001). The sky radiators consisted of uncovered copper tubes with aluminum fins, which were painted black and placed toward the sky on the roof of the house. The study showed that night-sky radiation worked well

under clear sky conditions in low relative humidity and at low wind speeds. The experimental results, in the long-term cool storage mode from the end of March to early May, showed that the tank water temperature can be decreased from about 50 °C (122 °F) to 10°C (50 °F) by sky radiation alone. The water temperature then was further decreased from 10°C (50°F) to 4°C (39°F) by a heat pump in order to be introduced to the fan coil units of the cooling system.

Khedari et al. (2000) conducted an experimental study of night-sky radiation cooling under tropical climate in Thailand. Four types of roofing materials were studied as radiators on the roof: 1) flat white painted metal sheet over CPAC Monier tiles (popular concrete roofing tiles in Thailand), 2) painted white CPAC Monier tiles, 3) CPAC Monier tiles, 4) white-painted, corrugated sheet metal over gypsum board and CAPC Monier tiles. The experimental results showed that the radiators type 1 and 4 (ones that have metal sheets over concrete tiles) performed better that type 2 and 3. Type 1 and 4 radiators yielded a maximum 6 °C (10.8 °F) temperature difference between the radiators' surfaces temperature and ambient temperature. However, the reported temperature difference graph, the surface temperatures of type 2 and 3 were only 1 to 2 °C (1.8-3.6 °F) higher that those of type 1 and 4. For space cooling, the study discussed air temperatures underneath the four radiators. The experimental results showed that the temperature of air below the metallic sheet (of type 1 and 4 roofings) was lower than the ambient air in the range of 1-3 °C (1.8-5.4 °F), while the temperatures of air below the roof without metallic sheet (type 2 and 3) were higher especially from sunset to about 9:30 P.M. The high temperatures in type 2 and 3 roofing, as reported, were mainly due to high thermal mass of concrete tiles. This study concluded that concrete tiles with metallic sheets may be used as a night space cooling strategy as they can lower the air temperature under the roof in the range of 1-3 °C (1.8-5.4 °F). This study, however, reported only surface temperatures and air temperature underneath those four radiators against ambient temperature. There was no investigation on the magnitude of radiative heat loss to the sky.

A night sky radiation strategy could be operated with the hybrid PV/T collector system by using existing resources that are already present in the system. It requires operating the system at night while electricity and hot water are produced in the daytime. The integration of the night sky radiation to the hybrid PV-T^2 collector system should yield more productivity of the system than the operation of the Hybrid PV-T^2 system alone. However, no attempt so far could be found to integrate it to a hybrid PV-T^2 collector system.

2.4 Analysis of Photovoltaic and Solar Collector Systems

Research concerned with the performance prediction of solar thermal systems, and photovoltaic systems was conducted in the 1970s – 1990s and is well documented in textbooks such as Duffie and Beckman (1991). F-Chart and PV F-Chart are two well accepted computer programs used for analysis and design of solar heating systems and photovoltaic systems respectively. Both programs were created by S.A. Klein and W.A. Beckman at the University of Wisconsin Solar Energy Laboratory. The F-Chart program uses the f-Chart method, which is a solar heating systems analysis method. The F-chart method provides a means for estimating the fraction of a total heating load that will be supplied by solar energy for a given solar heating system under specific operating conditions (Duffie and Beckman, 1991). PV F-Chart is a program that calculates the long-term average performance of PV systems, including: Stand-Alone Photovoltaic Systems, Utility Interface Systems, and Battery Storage Systems (Klein and Beckman, 2001). F-Chart and PV F-Chart will be used to analyze the performance of the hybrid PV-T system in this research. The details of using both programs are described in Chapter IV, Section 4.3.

2.5 Building Thermal Simulation

The proposed research is also concerned with the thermal simulation of buildings. Thermal simulations use dynamic heat loss/gain calculations, which require hourly calculations that involve the space load, energy required by the primary and secondary equipment of building systems, and typical weather conditions (ASHRAE, 2001). Since dynamic energy calculations are complex and require a significant amount of effort to be calculated by manual methods, computer programs are now routinely used to perform such calculations.

2.5.1 Building Energy Simulation Programs

The thermal simulation of buildings originated in the 1960s through the support of the U.S. government. In the U.S., two public domain, hourly building energy simulation programs, DOE-2 (LBNL, 1993) and BLAST (BSO, 1993), have been developed since the 1970s. Both programs are capable of performing a detailed analysis of the energy consumption in a building.

They both are comprised of hundreds of subroutines to simulate dynamic heat and mass flows of a building. They are widely used throughout the world. BLAST (Building Loads Analysis and System Thermodynamics) had been sponsored by the Department of Defense, which ended support for BLAST in 1995 due to budget constraints. DOE-2 which was sponsored by the U.S. Department of Energy (DOE), initially called the Post Office program was created in the late 1960s for the U.S. Post Office. Since then, its development has continued until the last version of DOE-2 was released in spring 2005.

DOE released a new building energy simulation program called EnergyPlus in the spring of 2001. EnergyPlus combines the most popular features and capabilities of BLAST and DOE-2. EnergyPlus also includes a number of new simulation features. Comparisons of the three programs show that EnergyPlus has the most features and capabilities such as sub-hourly user-definable time steps, improve ground heat transfer modeling using three-dimensional finite difference ground models, thermal comfort models based on activity, and anisotropic sky model for improve calculation of diffuse solar on tilted surfaces (Crawley et al., 2000). Due to such advantages and the free distribution of the EnergyPlus program, it is poised to become the most important building energy program ever created. However, EnergyPlus is now very new to the building thermal simulation community as compared with the DOE-2 which has been widely used and remains the most accepted. In summary, the thermal analysis of the case-study building will be performed using the DOE-2 building energy simulation program.

2.5.2 Calibrating Building Simulation Models

As mentioned earlier, DOE-2 will be used to perform the thermal analysis of the case-study house. To create a model that accurately represents a real building, adjustments of the model's inputs or calibration, is required to obtain an accurate simulation of an existing building under real weather conditions. Calibration techniques for hourly building simulation have been reported by many researchers over the years including Hsieh (1988), Hsieh et al. (1989), Haberl (1988), Kaplan et al. (1990a, 1990b, 1992), Hinchey (1991), Bronson et al. (1992), Bou-Saada and Haberl (1995), Manke et al. (1996), Haberl et al. (1998), and Haberl and Bou-Saada (1998).

Hsieh (1988) compared DOE-2 simulated temperatures with measured temperatures in order to help identify the discrepancy between the simulated and actual building energy use. Hsieh used the measured temperature data to specify thermostat values in the DOE-2 input file instead of using an averaged set point temperature. The result showed that using the measured

data helped reduced the discrepancy between the simulated and actual building energy use.

Hsieh et al. (1989) presented a study that included specific calibration procedures for improving building simulation using DOE-2. The study compared simulation results of two buildings with measured data. The comparison showed that occupant effects were the major sources of discrepancy between the simulated and measured data as the reported highest amount of error was due to the occupant use of lighting and equipment (the error was about 50%). HVAC operation schedule settings were found to be the second highest source of error. Hsieh proposed a method that can overcome the error caused by occupant use of lighting and equipment; electricity consumption was directly measured in offices for one week in order to help develop a daily energy use profile for that week. Calibration procedures also included a detail sensitivity analysis to help determine which building and HVAC system components have the greatest contribution to building energy use.

Kaplan et al. (1990a) proposed short-term measured data for calibrating a DOE-2 model. According to Kaplan, the short-term method provides a cost efficient alternative to analyze building energy performance. There were three calibration periods used to tune the models: a cold weather month, a hot weather month, and a moderate weather month. Kaplan noted that calibrating the model in a moderate month was very difficult due to the unpredictability of HVAC operation schedules and the instability of weather patterns. Thus, two periods of measured data (a cold weather month and a hot weather month) were found to provide the best results to calibrate the models.

In the process of modeling and calibrating a model to an actual building, researchers use graphical methods and statistical methods for comparing the simulated data of the model with the measured data of the actual building. Three-dimensional plots have even been used as a tool for calibration the model. Three studies used three-dimensional plots to display large amounts of hourly data in a simple and concise plot (Haberl et al., 1988; Haberl and Vajda, 1988; Haberl and Komor, 1990). Hinchey (1991) used three dimensional time-series plots showing “residuals” which is the differences between simulated data and measured data to assist with the calibration of the simulation. Simple comparisons of a simulated model to data from an actual building including bar charts, monthly x-y time-series graphs, and monthly percent difference plots (Bronson, 1992; Bronson et. al; 1992; Manke et al., 1996). Bou-Saada (1994) and Haberl and Bou-Saada (1998) presented several new techniques for improving calibrations including graphical methods and statistical methods. Graphical calibration methods included scatter plots and superimposed, juxtaposed binned, box-whisker-mean plots, which

were very helpful for comparing measured and simulated data. Binned box-whisker-mean plots presented profiles of mean and inter-quartile range which were very useful for comparing the trends of the two data sets. Data were also compared in different daytypes and periods. A 24-hour weather daytype bin analysis was performed for evaluation of hourly temperature and schedule dependent data comparisons. For long-term trends, 52-week bin analysis was performed. Several statistical calibration methods were used to as goodnees-of-fit indicators including a monthly mean difference, an hourly mean bias error (MBE) for each month, and hourly root mean squared error (RMSE) reported monthly, and hourly coefficient of variation of the root mean squared error (CV(RMSE)) (Kreider and Haberl, 1994).

2.6 Summary of Literature Review

This chapter has reviewed literature that is related to areas of interest of this research. The basis of thermal comfort serves as a guideline or criteria to assess thermal conditions in the case-study house and the improved model. For this research, ASHRAE Standard 55-1995 will be used to evaluate thermal comfort conditions of the case-study house. However humidity control to avoid the growth of microorganisms is significant, thus, the upper limit of 60 percent relative humidity of ASHRAE Standard 55-1992 is also a criterion to evaluate conditions of the case-study house. In addition to the ASHRAE Standard, the studies of Thai thermal comfort showed that Thai residents have a wider comfort range of temperature and exceed ASHRAE's summer comfort zone outward by 4 to 5.5 °C (7.2 to 9.9 °F). Thus, this study will also consider that the average Thai's thermal comfort temperature is relatively higher than those specified by ASHRAE.

The review of energy efficiency in housing in Thailand gave insight into the techniques or practices that were successful or recommended for improving energy efficiency in residential buildings. The results from the previous studies showed that improving the building envelope was the main concern and the most significant for improving the energy efficiency of the building. Light-weight concrete blocks were used in projects and studies instead of the typical concrete blocks and bricks. Shading devices, vegetation and landscape were also used to minimize the heat from outside (Boonyatikarn, 1999; Humanist Co. Ltd., 2000). Earth-cooling techniques were used in Boonyatikarn's house to reduce the cooling load of the air conditioning system on the ground floor (Boonyatikarn,1999). Studies by Parker (1991, 1995) showed that the reduction of heat transferred through the ceiling in Thai residential buildings is another

significant strategy for improving energy efficiency. By installation of 7.5 cm (2.95 inches) of fiberglass insulation in the ceiling, the size of air conditioning systems could be reduced by about 33% (Parker, 1991). Using more energy efficient air conditioning systems and improving the building's envelope may reduce energy use by the air conditioning systems by over 40% (Parker, 1995). From the review of the previous studies, improvements to the building envelop were shown to be significant means of reducing cooling energy use. Thus, improving building envelop strategies will be used to reduce energy use in this thesis.

Thailand's national development plans (8th and 9th National Social and Economic Development Plan) promote the use of renewable energy such as biomass and PV technologies, which has helped expand the use of residential PV systems. Although the use of PV in residential buildings is very low, it is expected to increase rapidly. Thus, this thesis also aims to study the use of PV systems in a Thai residential building which is the case-study of this research.

The review of hybrid PV-T systems provided background knowledge about these systems. There are theoretical and experimental studies of the hybrid PV-T systems that reported energy efficiency and other variables of the systems. One of significant results was an experimental study reported by Tripanagnostopoulos et al.(1996). In this study, glazing and a diffuse reflector (a flat aluminum sheet) were installed on a PV-T system. The results showed that thermal energy efficiency of the water heating was doubled, but the PV efficiency was decreased by about 10-20%. Another significant study is from a theoretical study by Garg and Agarwal (1995). The results showed that the optimum flow rate of water is about 0.5 gpm (the collector of 2 m^2 or 21.5 ft^2). Their model predicted the system performance at about 60-80 percent (with a glass cover), which agreed with a theoretical study by Bergene and Løvvik (1995). From experimental and theoretical studies, the thermal efficiencies of the PV-T systems (without a glass covered) were relatively low, which lowered the total efficiency of the systems. Studies reported that thermal efficiency of the systems was significantly increased by adding a sheet of glass on the PV-T panel. However, since this thesis also aimed to experiment with the heat rejection performance of the PV panel (without additional glazing), the experiment with a bare PV module seemed to be suitable.

There are theoretical and experimental studies and reports of night-sky radiation by several researchers including Martin (1989), Saitoh and Fujino (2001), and Khedari et al. (2000). One of significant results from those studies is an experimental study in a hot and humid climate (i.e., Bangkok, Thailand) by Khedari et al.(2000). In this study, metallic sheets

were installed on a concrete tile roof to help radiating heat from the roof to the sky. The experimental results showed that the metallic sheets could lower ambient air temperature under a concrete tile roof in the range of 1-3 °C (1.8-5.4 °F), while the temperatures of air below the roof without metallic sheets were higher than the ambient air temperature. However, from the reviewed literature, there was no attempt so far could be found to use a PV panel as a heat rejecter.

For analysis of photovoltaic and solar collector systems, F-Chart and PV F-Chart are two well accepted procedures for the analysis and design of solar heating systems and photovoltaic systems respectively. Thus, these programs will be used to analyze the performance of the hybrid PV-T system in this research.

The thermal analysis of the case-study building will be performed using the DOE-2 building energy simulation program. For model calibration, it is very significant to obtain measured data for indoor temperatures and the occupant use of lighting and equipment in order to create an accurate simulation model (Hsieh, 1988; 1989). From Kaplan et al. (1990a), short-term measured data in a cold weather month and a hot weather month were sufficient for calibrating a DOE-2 model. There are several graphical and statistical methods that have been used and very useful for calibrating the model (Haberl and Bou-Saada, 1998). Therefore, this thesis will use short-term measured data and statistical methods including MBE, RMSE, CV(RMSE) for calibrating the DOE-2 model.

CHAPTER III

SIGNIFICANCE AND LIMITATIONS

3.1 Expected Contributions from this Research

This research is expected to provide the following benefits to the development of residential buildings in Thailand.

1) The study will improve the understanding of a typical Thai residential building (base-case house), including its thermal conditions and energy use.

2) Reduced energy use and improved thermal conditions for the base-case house using the DOE-2 simulation program.

3) A guidelines to assist architects and engineers for designing energy-efficient houses in Thailand's environment.

4) Experimental results from a PV-T^2 collector system including solar thermal collector performance and photovoltaic performance.

5) Experimental results from a PV-T^2 collector system used as a heat rejection device.

3.2 Scope and Limitations of the Research

1) The building energy simulation in this thesis is limited to the capabilities of the DOE-2.1e version 119.

2) The solar thermal analysis in this thesis is limited to the specific types of systems that can be analyzed with F-CHART.

3) The PV analysis is limited to the analysis using PV F-CHART.

4) The experimental results of thermal performance of the hybrid PV-T^2 system are limited to the meteorological conditions experienced during the period from November 6, 2002 to July 3, 2003 in College Station, Texas.

5) The experimental results of electricity production of the hybrid PV-T^2 system are limited to meteorological condition experienced during the period from December 20, 2002 to June 7, 2003 in College Station, Texas.

6) The experimental results of heat rejection performance of the hybrid PV-T^2 system are limited to meteorological condition experienced during the period from April 25, 2003 to June 7, 2003 in College Station, Texas.

CHAPTER IV

METHODOLOGY

This chapter discusses the four research methods used in this research: 1) Measurements and analysis of a case-study house, 2) Field experiments of a hybrid PV-T^2 collector system, 3) Building thermal simulations, and 4) Economic analysis. Each of these research methods are summarized and presented in Figure 4.1. The details of each method are described in the following sections.

4.1 Case-Study House

A typical contemporary Thai detached house was selected as a case-study house. The characteristics of this house are described in Section 4.1.1 and 4.1.2 including: building information, building energy use, thermal conditions of spaces in the building, and weather data.

4.1.1 Selection of the Case-Study House

The selection of the case-study house is based on three criteria: 1) location, 2) characteristics of the house and 3) the number of occupants. Detailed criteria are discussed below.

4.1.1.1 Location of the Case-study House

Thailand lies on the Indochinese Peninsula from about 5° to 20° south latitudes and about 98° to 105° east longitude (see Figure 4.2), which is about 1,100 miles from north to south and about 485 miles from east to west. Thailand's geography is diversified from the long coast and mountains of the southern region to the flat land of the central plain region to the high elevation and mountains in the northern region, and includes a large plateau in the northeast region (FOA, 1981). Thailand's weather is also diversified. The central plain region is the largest region located in the middle of the country. It is subdivided into three geographic subregions; the southeastern region, the northern rolling plains region, and the Chao Phraya

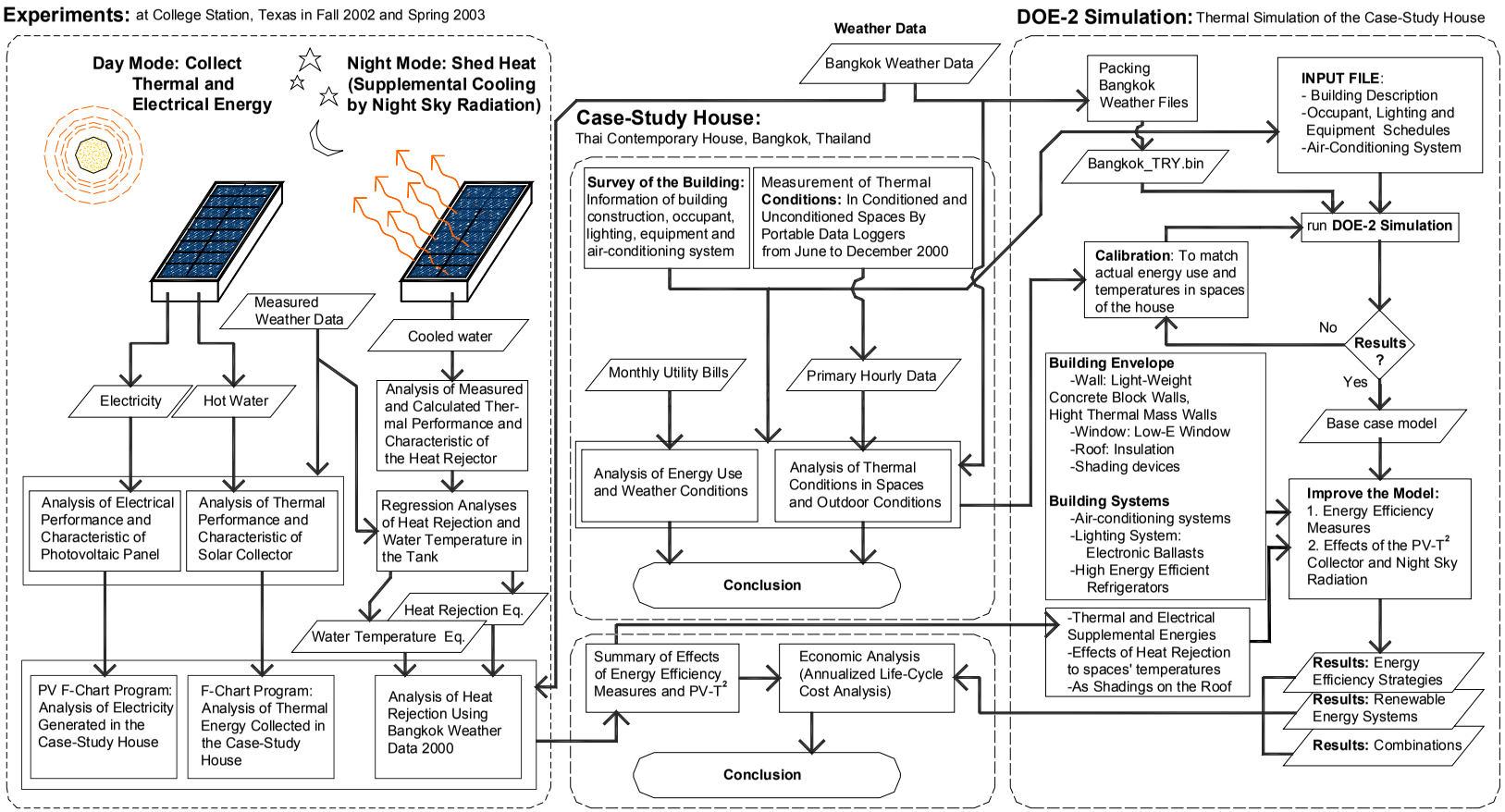


Figure 4.1 *Research Methods Diagram.*

delta, which is the largest fertile, lowland area of the country (FAO, 1981). Bangkok and vicinity area, which is the most populated area of the country, is in this subregion (NSO, 2000b). Therefore, this research will use a case-study house that is located in Bangkok or the vicinity of Bangkok.

Another consideration for selecting a case-study house is the solar radiation. Figure 4.3 shows the average daily solar radiation on a horizontal surface from January to December. According to Figure 4.3, the average daily solar radiation ranges from 16 to 21 $MJ/m^2 \cdot day$. The majority of Thailand is in the 18 MJ/m^2-day region. There is a vast area of the central plain that is in the 18 MJ/m^2-day insolation range as well. Therefore, the desired location of the case-study house is in the Cha Phraya delta subregion with an average daily horizontal solar radiation of 18 MJ/m^2.

4.1.1.2 Characteristics of the Case-study House

This research aims to investigate a typical contemporary, detached Thai house, which has characteristics defined by Thongpiyapoom (1996). The general characteristics are the following:

-Two-story building with pitched roof covered with concrete tile.

-Three-bedrooms with three-bathrooms.

-Walls constructed of four-inch thick brick coated with white-colored cement.

-Concrete columns, beams, and floors.

-Wood frame casement windows with single-pane tinted glass.

4.1.1.3 Number of Occupants

People exchange heat with the environment. A resting adult produces about 350 Btus of heat per hour (ASHRAE, 2001 p.8.1). Thus, the number of residents affects the thermal condition in a building. People also require fresh air, as well as comfort conditions. The average Thai household has 3.6 persons per house (NSO, 2000b). Thus, the preferred number of occupants in the case-study house is three to four persons.

Figure 4.2 *Map of Thailand (Courtesy of The General Libraries, The University of Texas at Austin.).*

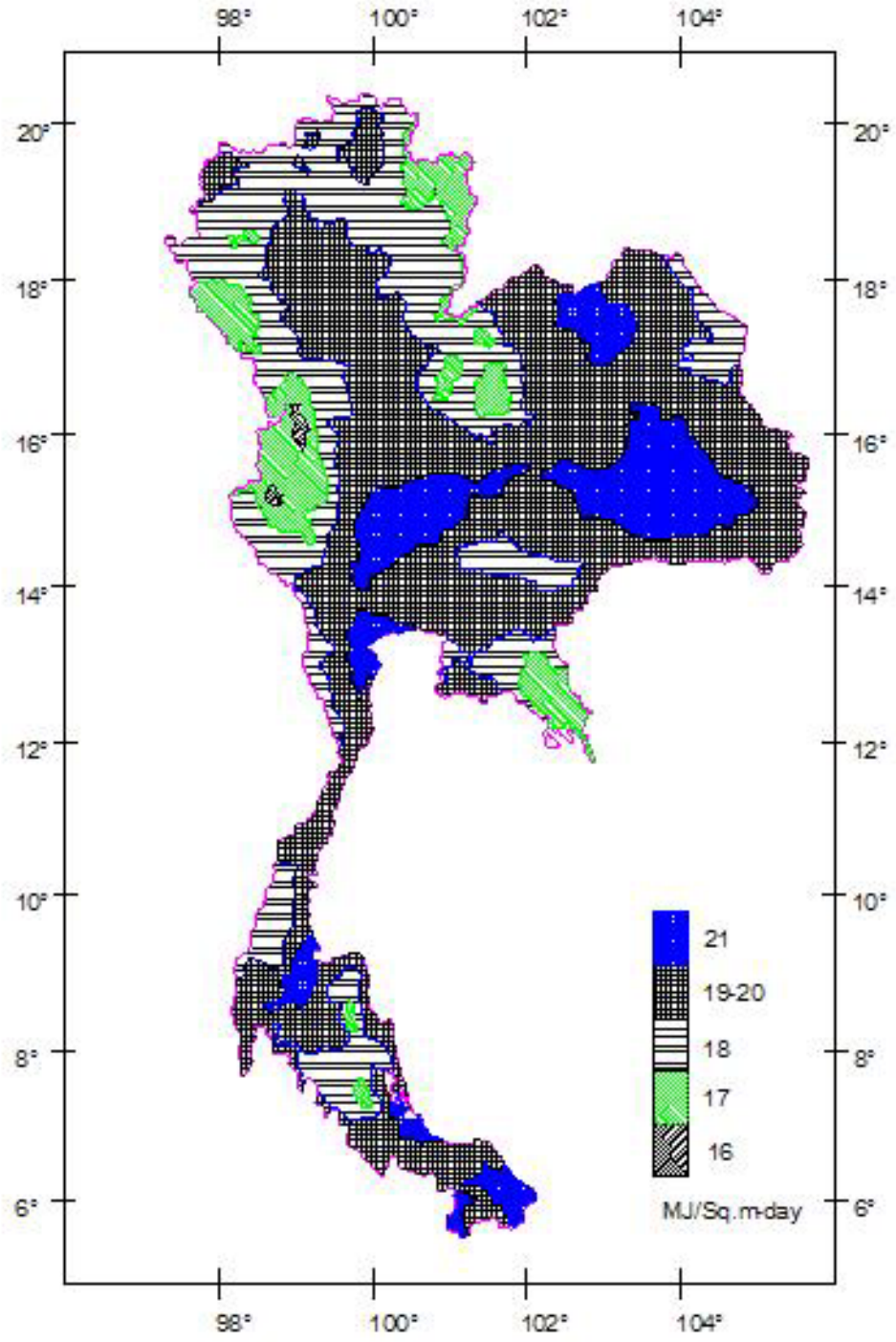


Figure 4.3 *Thailand's Solar Map: average daily solar radiation on a horizontal surface from January to December. (This figure was redrawn by the author from Thailand's solar data published by NEPO (2000)).*

4.1.2 Data Collection for the Case-Study House

As presented in Figure 4.1, the required data and information for the case-study house can be classified in three categories: building information, building's energy use, and climate data.

A typical contemporary Thai detached house, which met the previously mentioned criteria, was selected as a case study. Building information includes the building description, types and properties of the materials, and construction. To acquire this information the building was surveyed and photographed. Construction drawings of the building were obtained as well. After surveying the type of building materials, the thermal properties of the materials were obtained from LBNL (1982, 1993), Stein and Reynolds (1992), Watson, D. (1993), and the Thai Gypsum Products Public Company Limited (1996).

The monthly utility bills (from June to December 2000) from the case-study house were then collected. Energy use data from single-family homes in Bangkok and the vicinity of Bangkok were also obtained from the Metropolitan Electricity Authority of Thailand (2000) and the National Statistical Office of Thailand (NSO, 2000a). Energy use from both sources is presented in the next chapter.

The required weather data was categorized into two levels: macroclimate and microclimate. Bangkok weather data was acquired as macroclimate data, which included air temperature, relative humidity, solar radiation, and wind speed. The hourly weather data of Bangkok for the year 2000 was obtained from the Thai Meteorological Department, including dry-bulb temperature, relative humidity, wind speed, and solar radiation. These hourly weather data were then used to create the weather file, which was used in the calibrated building simulation.

The microclimate data included measurements of the interior conditions in the case-study house. These data were obtained by on-site measurements inside the case-study house. Four measurement devices (portable data loggers) for measuring and recording temperature and humidity were installed in the case-study building, including: one in an air-conditioned space, two in unconditioned spaces (1st floor and 2nd floor spaces), and one in the attic space. Microclimate data, which presents the thermal conditions of the house, was then compared with ASHRAE's thermal comfort standard (ASHRAE, 1995, 2001). The measured thermal conditions and the results of Thai thermal comfort studies by Busch (1990) and Jitkhajornwanich (1998) are also discussed in the next chapter. The amount of monthly

energy use indicated by the utility bills was averaged to daily energy use by dividing by the days in the month and then plotted against the average daily ambient temperatures for the utility billing period. Plots of monthly daily averaged energy use versus daily ambient temperatures show the effect of outside air temperature on the energy use of the house.

4.1.3 Instrument Calibrations

Portable data loggers were used to measure the temperature and humidity of the case-study house. Calibrations of both types of measurements were performed to ensure accurate measurements. Temperature sensors were calibrated with a calibrated hand-held Type-T thermocouple. The thermocouple was calibrated with ice-point and water boiling-point temperatures (Wise, and Soulen, 1986). Distilled water was used to make the ice and boiling water. Calibration of the humidity sensors used a method of humidity control by chemical salts that is described by Greenspan (1976). The results of the calibrations are presented in the Appendix C.

4.2 Experiment of the Hybrid Photovoltaic-Thermal (PV-T^2) Collector

One of the objectives of this research was to develop a hybrid photovoltaic-thermal (PV-T^2) collector system that can simultaneously convert solar energy to electricity and produce hot water (for domestic hot water supply) in the daytime, as well as radiate heat to the night sky. To accomplish these objectives, an experimental test box of a hybrid PV-T^2 panel was designed and constructed, and experiments conducted. The following sections explain the experimentation, the experimental box, its components, the system's test procedures, and the data collection.

4.2.1 Design of the Experiments

As mentioned in the literature review on hybrid PV-T systems, there are basically two types of heat transfer systems that are defined by their heat transfer media: air or water. Since one of the objectives of the hybrid PV-T system is to be able to produce domestic hot water (DHW), a water-type system was chosen. The liquid system also has an advantage over the air-type system namely, the direct heat transfer between collected heat and the potable water. The tested system was included to collect thermal and electrical energy during the daytime and

to reject heat during nighttime. Thus, experiments on the hybrid PV-T^2 system had two operating modes: day mode and night mode. The day mode use the photovoltaic panel as a dual energy collector unit (electrical and thermal energy). The night mode used the same photovoltaic panel as a heat rejection unit.

4.2.1.1 Day Mode Experiment

In the day mode, the collector unit collects solar energy and coverts it to electricity and thermal energy. In the experimental setup a photovoltaic (PV) panel was used to collect solar energy and convert it to electricity, and thermal energy was extracted from the PV panel through a heat exchanger system that is integrated into the PV panel (see Appendix B, B.1: Experimental Box for construction of the hybrid PV-T^2).

In the day mode experiments, a supply of "cool" water to be heated was prepared the night before the day mode experiment day. Experiments were then run to determine the necessary input parameters for running F-CHART. The electricity produced by the PV panel was measured on a series of days with varying panel temperatures to determine the necessary performance parameters for running PV F-CHART. To set up the day mode thermal collection, the night before the experiment, the water temperature in the Hot Tank was lowered to a temperature that was controlled by a submersed external thermostat, with heat rejected using a radiator with a blower. In the actual experiment, the thermostat was set to the lowest set-point temperature and the pump and the radiator were run all night, so the water temperature could reach the lowest temperature each night. This also solved a technical problem when the pump was not continuously run, since the pump would lose its prime and stop pumping when the thermostat was satisfied, making it unable to start again without priming. To cool the water in the Hot Tank, pump# B and the fan inside the radiator were turned on, while valve# 10 and 11 are open (see Figure 4.4 and 4.5). This allowed water to circulate in a loop from the Hot Tank to the radiator and back to the tank, removing heat from the water, which resulted in decreasing water temperature.

After the water in the Hot Tank is prepared for the day mode experiment, the experiment could be started in the morning when the sun rose. The experiment started with checking the water level and temperature in the Hot Tank using a calibrated liquid-in-glass thermometer. The tank can contain approximately five gallons of water. However, the water level was set at four gallons in each experiment to allow space above the water level for supply

and return piping. Variations in the initial water temperature corresponded to variations in the ambient temperature. Initial water temperatures will be further discussed in Chapter VII.

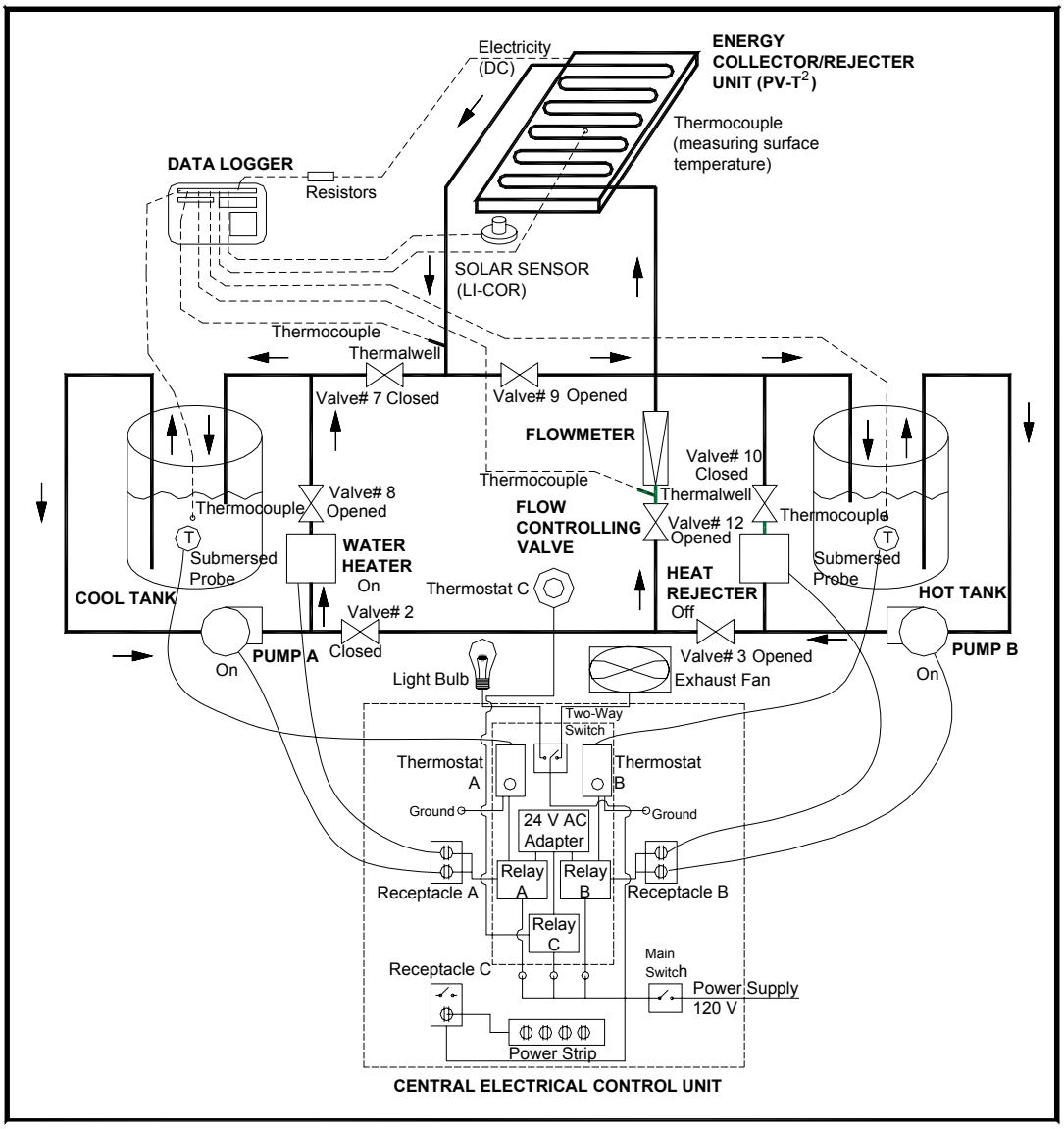


Figure 4.4 *Day Mode Experiment Diagram.*

Starting the day mode experiment consisted of turning on/off several devices, opening/closing different valves, and adjusting water flow rates at the globe valve (Valve# 12) (see Figures 4.4 and 4.5). The procedure to run the day mode experiment is listed below:

1. Turn on pump# B by adjusting the temperature set-point of thermostat B to the highest temperature, so the pump will be continuously running to maximize the exposure time of the circulating water to the heat collected in the PV panel.

2. Open valves#: 3, 4, 5, 9, 11

3. Adjust water flow rate at valve# 12 to the appropriate flow rate (the experimental flow rate was 1 gallon per minute)

Once the pump is on and the valves are opened or adjusted, water is circulated from the Hot Tank through valve# 11, to pump# B, to valve# 3, 4, 12, to the collector unit, to valve# 5, 9, and back to the Hot tank (see Figures 4.4 and 4.5). During the daytime of day mode experiment, if a night mode experiment is to be performed the following evening, then the water temperature of the Cool Tank also needs to be prepared. Preparation of the night mode experiment during the day time is explained in the next section.

4.2.1.2 Night Mode Experiment

In the night mode, the heat rejection experiment uses the collector unit as a heat rejecter. The water is heated as a batch during the previous day to approximately the same temperature using the compact water heater of the system. The hybrid PV-T^2 unit rejects energy through the collector panel by convection and long-wave radiation to the ambient.

As mentioned earlier, in the daytime prior to a heat-rejection experiment, water for experimenting in the night mode needs to be heated to a pre-determined temperature. To accomplish this, the water temperature of the Cool Tank is controlled by a submersed thermostat which activated a water heater. For heating the water in the Cool Tank, pump# 1 and the water heater are turned on; while valves# 1 and 8 are open (see Figures 4.5 and 4.6). The water is then heated as it circulates from the Cool Tank to the water heater and back to the tank.

Several other preparations were needed before a heat rejection experiment could be performed. First, during the early night mode experiments, it was observed that stored heat in

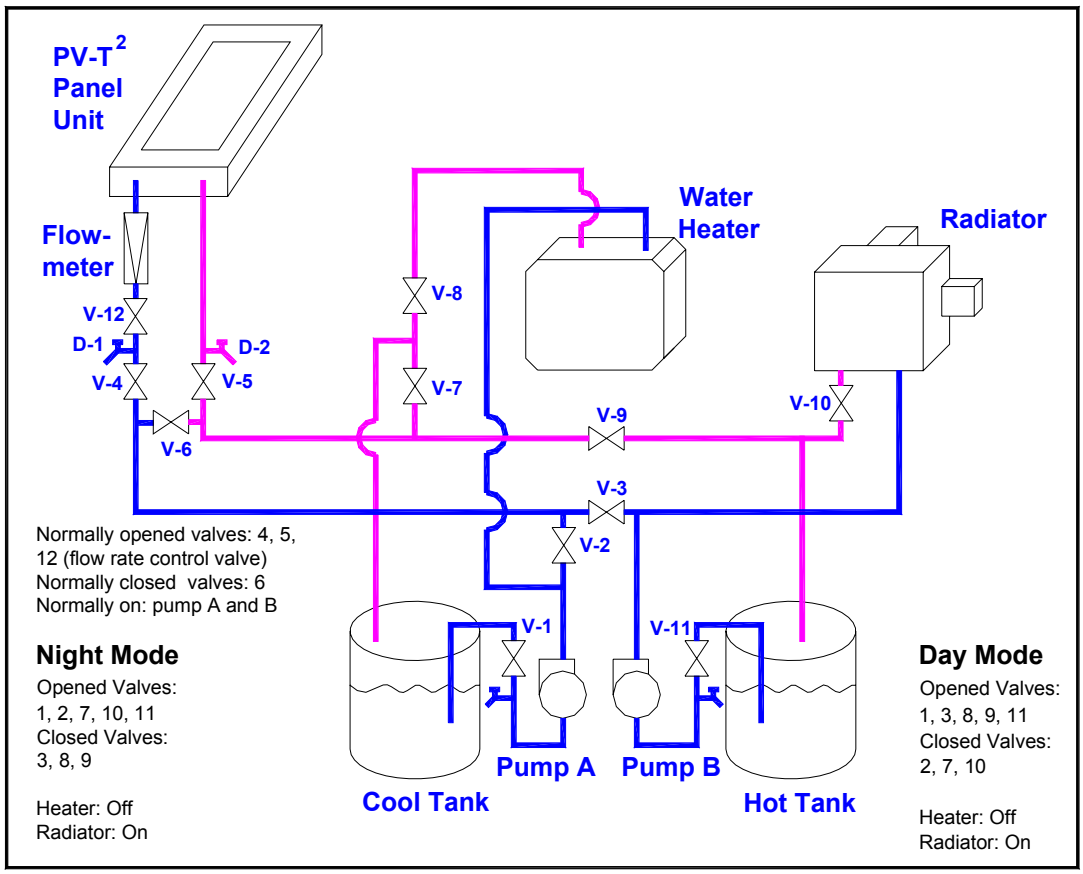


Figure 4.5 *Day Mode and Night Mode Valve Control Diagram.*

the body of collector/rejecter unit, from solar radiation or high ambient temperatures during the day time, had an adverse effect on the night mode experiment. The heat stored in the hybrid PV-T^2 collector during the daytime produced erroneous results in the first hour of the night mode experiments. Therefore, the temperature readings and rejected heat in the first hour could not be used for the system's performance assessment. To resolve this problem with the heat stored in the hybrid PV-T^2 collector, a well insulated aluminum shield was used to cover the hybrid PV-T^2 collector during the day before a nighttime heat rejection experiment was to be performed.

After the water in the Cool Tank was prepared, the night mode experiment was started in the evening when the sun went down. Like the day mode experiment, the surface of the PV panel needed be clean to ensure the consistent exposure to the sky each night the experiment

was conducted. The experiment started with checking the water level and temperature in the Cool Tank using a calibrated liquid-in-glass thermometer. The water level in the Cool Tank was kept at 4 gallons. Prior to the experiment the water in the Cool Tank was heated to 130-140 ºF, which also happened to be the maximum temperature of the water heater.

The procedure for starting the night mode experiment is listed below:

1. Turn on pump# A by adjusting the temperature set-point of thermostat B to the lowest temperature, so the pump will run continuously to maximize the exposure time of the circulating water to the ambient air and night sky.

2. Turn on valves#: 1,2,7,10, and 11.

3. Adjust the water flow rate at valve# 12 (the best experimented flow rates was determined to be 1.0 GPM)

Once the pump is on and the valves are opened or adjusted, water is circulated from the Cool Tank through valve# 1, to pump# A, to valves# 2, 4, 12, to the collector unit, to valve# 7, and back to the Cool Tank.

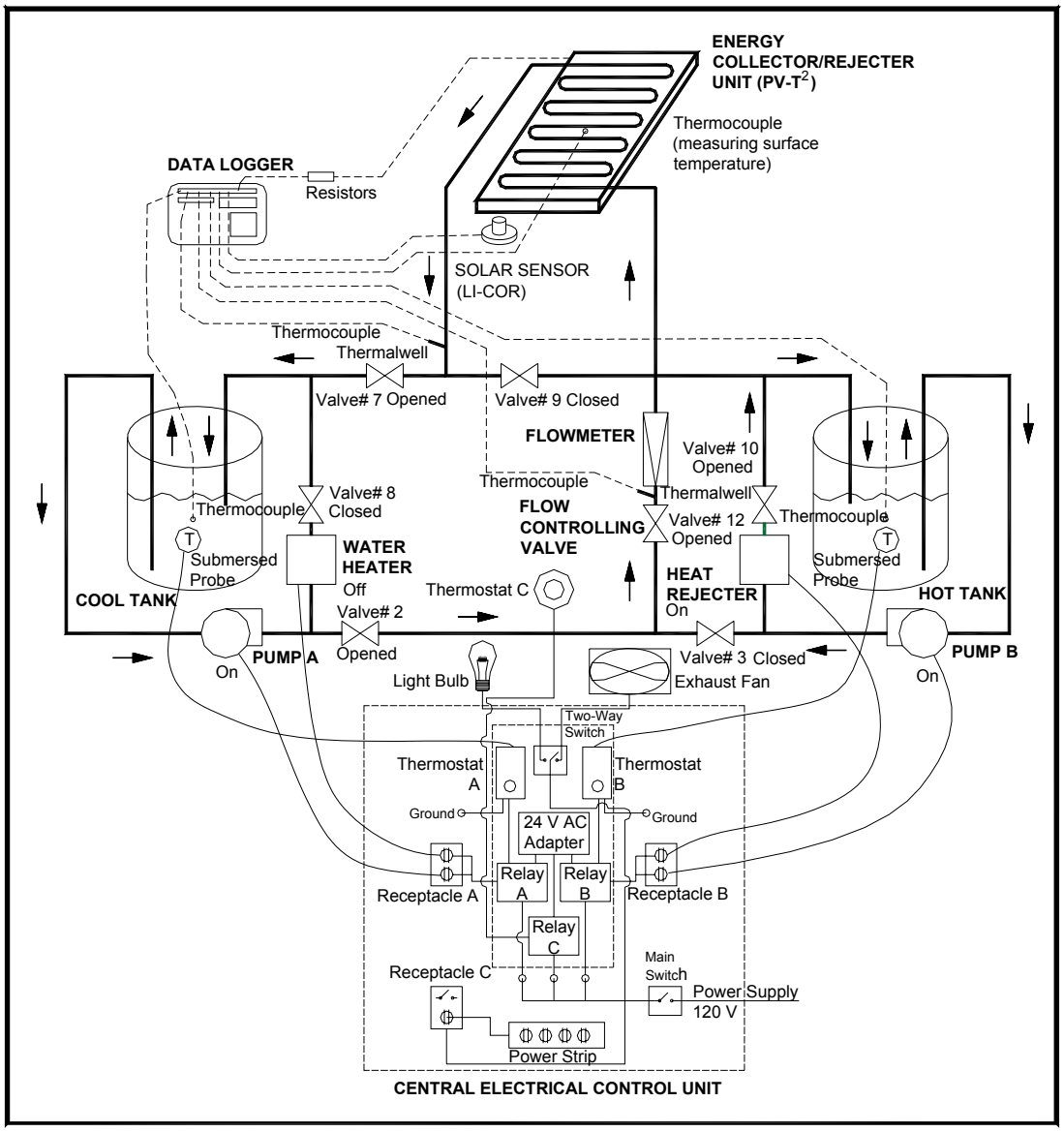


Figure 4.6 *Night Mode Experiment Diagram.*

4.2.2 Experimental Box

The experimental box was designed and constructed during the spring semester of 2001 through summer semester 2002. The experimental box was initially constructed in the Architecture woodshop. It was designed to be able to be disassembled in order to move it from

the woodshop to the solar test platform which is on the roof of the Langford Architecture Building A. Figure 4.7 shows the finished experimental box, solar test bench, and Dr. Kie Whan Oh's experimental box (Oh, 2000) on the solar test platform.

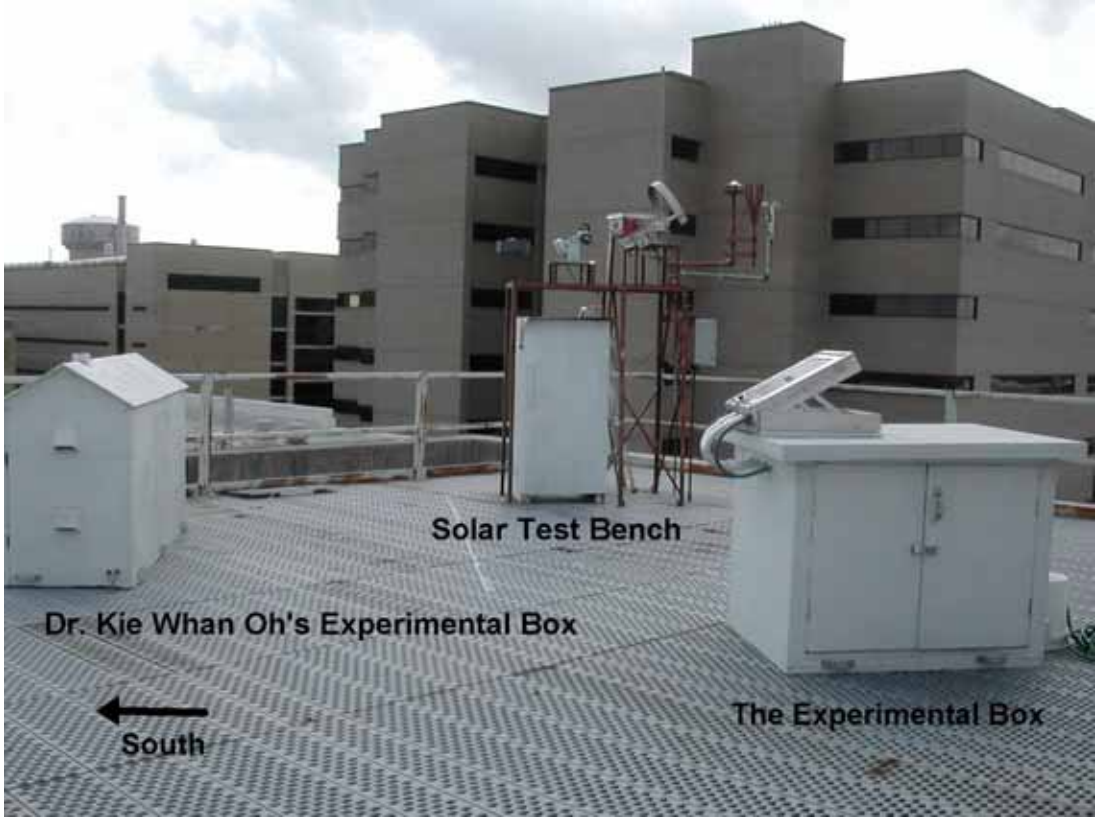


Figure 4.7 *Experimental Box and Solar Test Bench (View from the East).*

The hybrid PV-T^2 collector system consists of five sub-systems: 1) an energy collector/rejecter unit (PV-T^2 unit), 2) piping and heat storing systems, 3) a central electrical control system 4) a water temperature regulating system, and 5) a data acquisition system. All of these sub-systems are housed in the experimental box, except the energy collector unit, which is situated on the top of the box.

Figures 4.8 and 4.9 show the experimental box viewed from the southeast and northwest respectively. In Figure 4.8, the hybrid PV- T^2 collector unit, part of the piping system, and thermocouple can be seen in the picture. Figure 4.10 shows the systems that are inside the experimental box. The construction of the experimental box is presented in Appendix B.

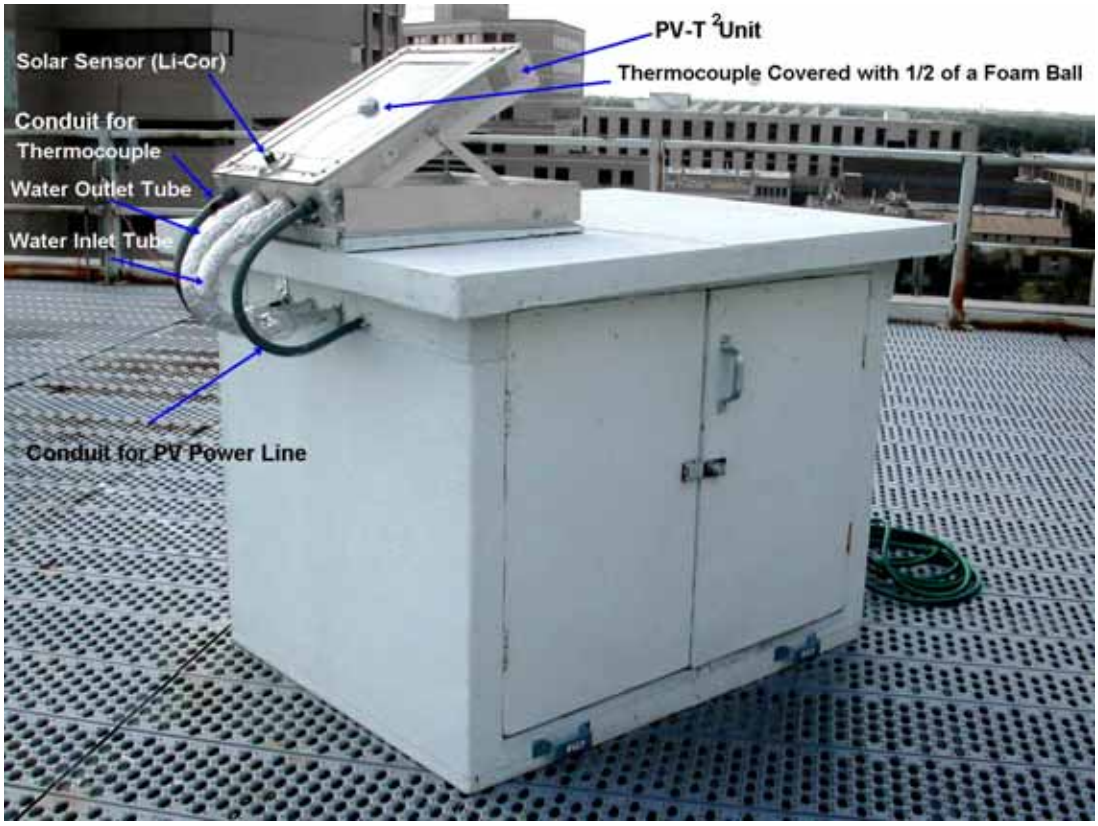


Figure 4.8 *Experimental Box (View from the Southeast).*

Figure 4.9 *Experimental Box (View from the Northwest).*

4.2.2.1 Energy Collector/Rejecter (PV-T^2) Unit

The energy collector/rejecter was designed to be a hybrid PV-T collector in the day time and a heat rejecter at night. It is comprised of a photovoltaic (PV) module, a heat exchanger plate, pipes, insulation, and a frame and supports (see Figure 4.11). A small polycrystalline PV module (Solarex SX-10) was selected as the photovoltaic collector panel for the system. It has a maximum power output of 10 Watts. The description of the PV module including the electrical characteristics and physical dimensions is presented in Appendix B.

The heat exchanger is basically two thin copper plates soldered with 3/8 inch copper pipe (see Appendix C). It was salvaged from the collector plate of a liquid-type solar collector. The heat exchanger was fastened to the back of the PV panel that was mounted on a steel plate and a aluminum frame. A high thermal conductance paste was used to improve the heat transfer

Figure 4.10 *Inside the Experimental Box (View from the East). The experimental box houses four systems that are described in this chapter. As seen in this picture, the left tank is the Cool Tank used in night mode experiment, and the right tank is the Hot Tank used in day mode experiment. The water heater is hung on the wall in the middle of the box. Piping systems run mostly on the walls and on the floor at in the back of the box. On the left door is the cover of the PV-T^2 units. On the right door are the system operating procedures and tool storage.*

efficiency between the PV module and the heat exchanger. The high thermal conductance paste is commercially called "Type 44 Heat Sink Compound" made by GC Electronics (GC Electronics, 2003). The heat sink compound is a good conductor, with a thermal conductivity of 5.22 $ft^2 \cdot h \cdot F/Btu \cdot in$, but it is not an adhesive material. Therefore, a metal bar, which was connected to the aluminum frame, was installed to press the heat exchanger plates down onto the back of the PV module. Between the bar and the heat exchanger plates, an insulator was inserted to avoid unwanted heat transferring out of the system.

The PV-T^2 unit is connected to heat storing systems (i.e., the Hot Tank and Cool Tank) through a piping system, which is described in the next section. In Figure 4.11, two insulated rubber tubes, which are wrapped with aluminum tape, are the flexible inlet and outlet connections to the collector. The insulation helps minimize the heat loss through the rubber tubes. The aluminum tape protects the insulation from solar radiation, and it also serves as cladding for the tubes to protect them from the weather.

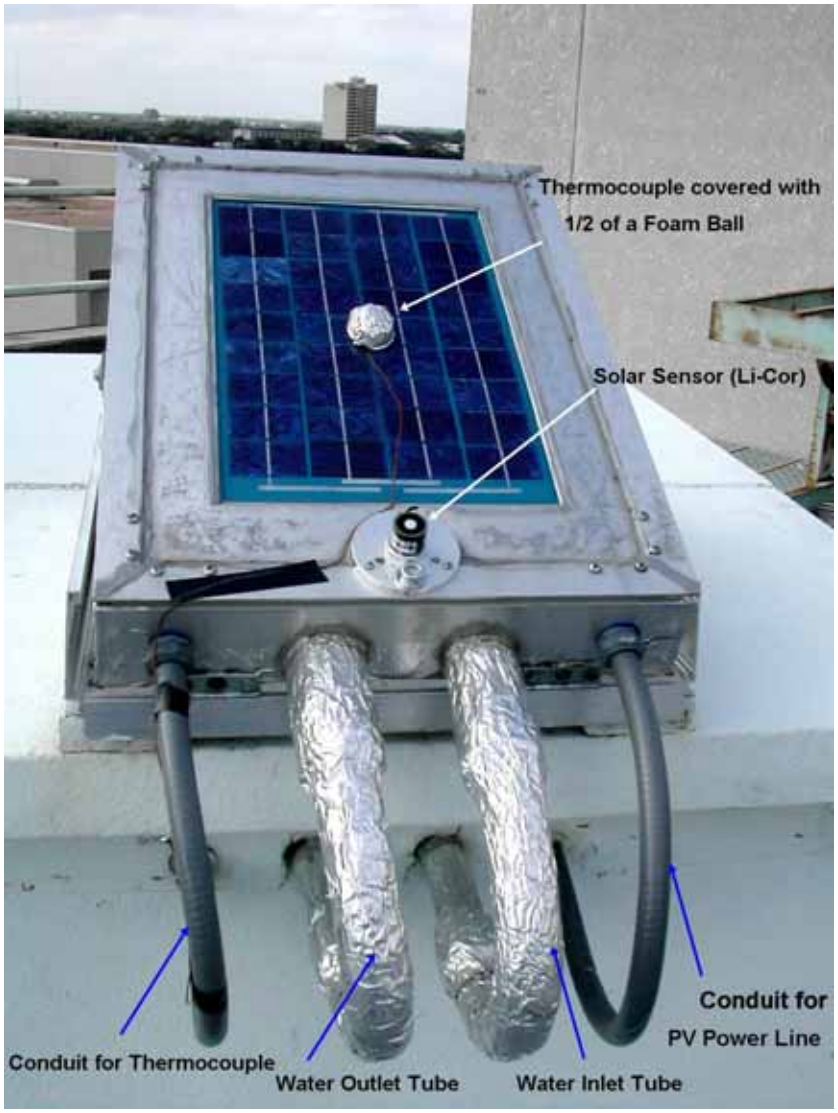


Figure 4.11 *Photovoltaic-Thermal Collector/Rejecter (PV-T^2) Unit.*

There are also two weather-proof conduits that are connected to the PV-T^2 unit. In Figure 4.11, the left gray flexible conduit is for a thermocouple line and a solar radiation sensor line, and the other conduit (right) is for the PV's power output line. The thermocouple in the left conduit was used to measure temperature at the back of the PV module. The head of thermocouple was inserted in between the back of the PV module and the heat exchanger plates. It was positioned in the middle of the module. A silicon photodiode type pyranometer (LI-COR, Inc., 1991), which was installed on the PV-T^2 unit, was used for measuring solar radiation in the plane of the collector.

There was also a thermocouple that was used to measure the front surface temperature of the PV module. It was installed in the middle of the collector's front surface, roughly opposite to the thermocouple inside the collector's module (see Figure 4.11). The head of the thermocouple was attached to the PV's surface with aluminum tape, which was then covered with ½ of a foam ball and aluminum tape to prevent the influence of the solar radiation and ambient air temperature at the surface. Silicone was used to attach the foam ball to the collector's surface.

4.2.2.2 Heat Storage and Piping Systems

The Hot Tank and Cool Tank were regular drinking water/ice tanks that were used for storing water in the experiments (manufactured by the Igloo Corp., Houston, Texas). The Hot Tank contains water that is used for storing heat in the Day mode. The Cool Tank contains water that is used for shedding heat in the Night mode. The tanks are 5-gallon tanks suitable for hot or cold liquids. The operating level of water in the experiments, in both Day mode and Night mode, is four gallons in each tank. Space above the water level (at four gallons) in each tank was allowed for inserting the supply and return piping.

The purpose of the piping systems is to circulate heat from the Hot Tank and the Cool Tank to the other devices including the PV-T^2 unit. There are four piping loops in the system: two main loops are for circulating water from the Hot and Cool Tanks to the PV-T^2 collector, one loop is for circulating the Hot Tank to the heat rejecter box, and one loop is for circulating water from the Cool Tank to the compact water heater (see Figure 4.5). All of the piping loops share various pipes, valves and pumps. All pipes were ½ inch copper pipes. Valves were installed for controlling the direction of the flow of the water. The valves also help prevent water from draining back into the tanks when the system was not operating. This is important

since the volume of water in the pipes above the tanks when combined with an already full tank exceeded the tank capacity. Hence, when the pumps were off, the valves were shut to prevent backflow into the tanks. In the worst case, air would enter the pipes, causing the pump to lose its prime. There are 2 water pumps in the system: one (pump# A) for the Cool Tank and another (pump# B) for the Hot Tank. Pump# A was used to pump water from the Cool Tank to the PV-T^2 unit, or to the compact water heater. (see Figures 4.5 and 4.12). Pump# B was used to pump water from the Hot Tank to the PV-T^2 collector, or to the heat rejection unit (see Figures 4.5 and 4.14).

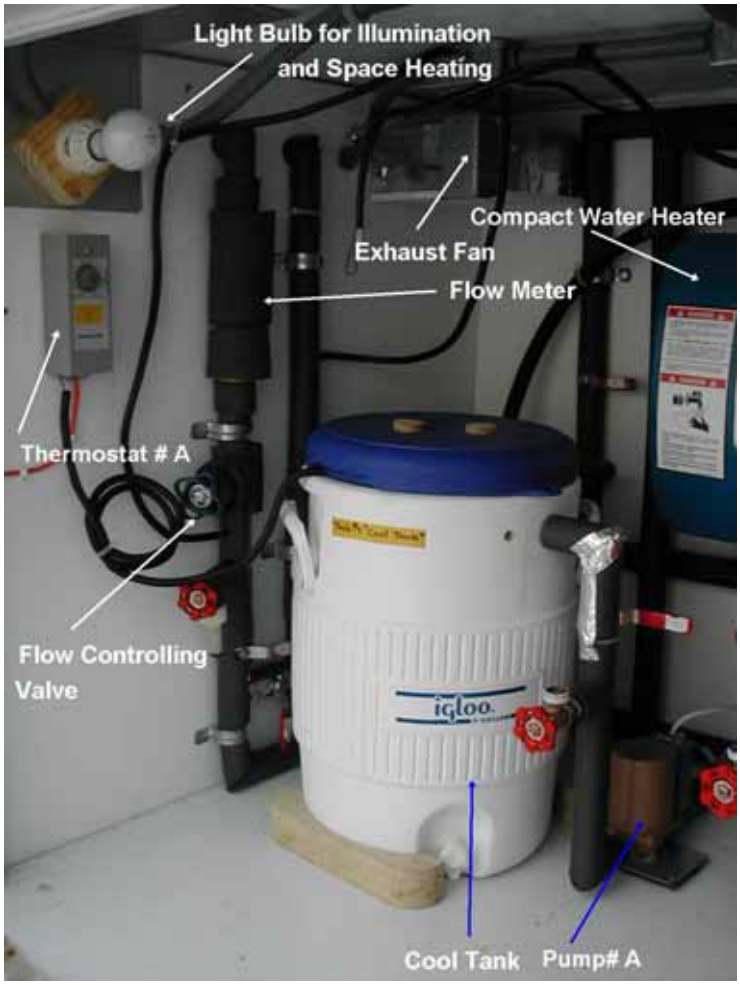


Figure 4.12 *Heat Storage (Cool Tank) and Piping System (See Close-up of the Flow Meter in Figure 4.13).*

Another component of the piping system is a water flow meter, which shows the flow rate controlled by the globe valve installed directly below the flow meter (see Figures 4.12 and 4.13). After the flow meter was installed in the piping system, its flow rate measurement was cross checked.

Figure 4.13 *Close-up of the Flow Meter. The flow meter was designed for solar hot water system. The flow rate scale ranged from 0 to 10 GPM. However, the maximum flow rate was about 1 GPM. Unfortunately, this low flow was at the very bottom of the scale. Therefore, a new scale was determined and experimentally marked on masking tape on the lower part of the flow meter.*

Figure 4.14 *Heat Storage (Hot Tank) and Piping System.*

4.2.2.3 Central Electrical Control Unit

The Central Electrical Control Unit (CECU) is where the electricity is brought in and distributed to all other devices which are pumps, exhaust fan, light bulb, water heater, blower in the radiator unit, data logger, and electrical circuit. Figure 4.15 shows the CECU; the gray box

was opened for the photograph (normally there is a cover on the box). The diagram of the CECU is shown in Figures 4.4 and 4.6.

Figure 4.15 *Central Electrical Control Unit.*

The Central Electrical Control Unit consists of a main switch, three electromechanical switches (relays), five receptacles, two switches, and a 120V to 24V transformer. The main switch controls distribution of electricity from the power line to the experiment box. From the main switch, electricity (120 V) is distributed to the relays, and to a combined receptacle/switch

(receptacle C). Receptacle C is an electrical outlet for other external devices such as a laptop computer that may need power supply while connected to the data logger. The light switch in Receptacle C is for turning the light on or off. This light also served to warm the interior of the box during freezing conditions.

Relays A and B are configured in the same way; each one is connected to a thermostat and two receptacles. For instance, Relay A is connected to Receptacle A and Thermostat A. Those are called "Control Set A". Control Set A is for controlling electrical current flow to the water heater and Pump A. The relays are powered by the 24V transformer. The relays' contacts are normally open (NO) type. When the thermostats reach the set-point temperature, they signal the relay to close the contact. In this mode, the 120 VAC circuit is energized and the power is supplied to the electric devices that are plugged in.

The Control Set C works in the same way as the Control Sets A and B except that Relay 3 is directly connected to an exhaust fan and a light. In Control Set C, there is a two-way switch that is used to switch between heating mode (use of the light) and cooling mode (use of exhaust fan) to regulate the air temperature inside the experiment box. Control Set C is called the Interior Temperature Control System. The Interior Temperature Control System is to prevent the interior air temperature from extreme conditions. The thermostat can be set in the cooling mode (summer) or heating mode (winter) at a pre-determined set-point temperature. On cold days, the heating mode is selected, and the thermostat can be set at 40 °F. The light is turned-on whenever the temperature drops below the set-point temperature. On hot days, when the cooling mode is selected, the thermostat can be set at 100 °F. The exhaust fan is then turned-on whenever the temperature rises above to the set-point temperature.

4.2.2.4 Water Temperature Regulating Systems

As mentioned in Section 4.1.2, water in both the Hot and Cool Tanks needs to be cooled or heated to a temperature before conducting the experiments. The systems to perform such tasks are called the Water Temperature Regulating Systems. There are two separate systems for each experiment or mode (Day Mode and Night Mode) to regulate the water temperature in each tank. The Day Mode system consists of a heat rejection box and Control Set B of the Central Electrical Control Units (see Figure 4.16). The heat rejection box was custom made from an automobile radiator, a blower, and aluminum plates. The construction of the heat rejection box is described in the Appendix B. The Night Mode system consists of an instantaneous, compact water heater, which is controlled by Control Set A of the Central

Electrical Control Units. The operation of the Water Temperature Regulating Systems in the Day Mode and the Night Mode was described earlier in Sections 4.2.1.1 and 4.2.1.2 respectively.

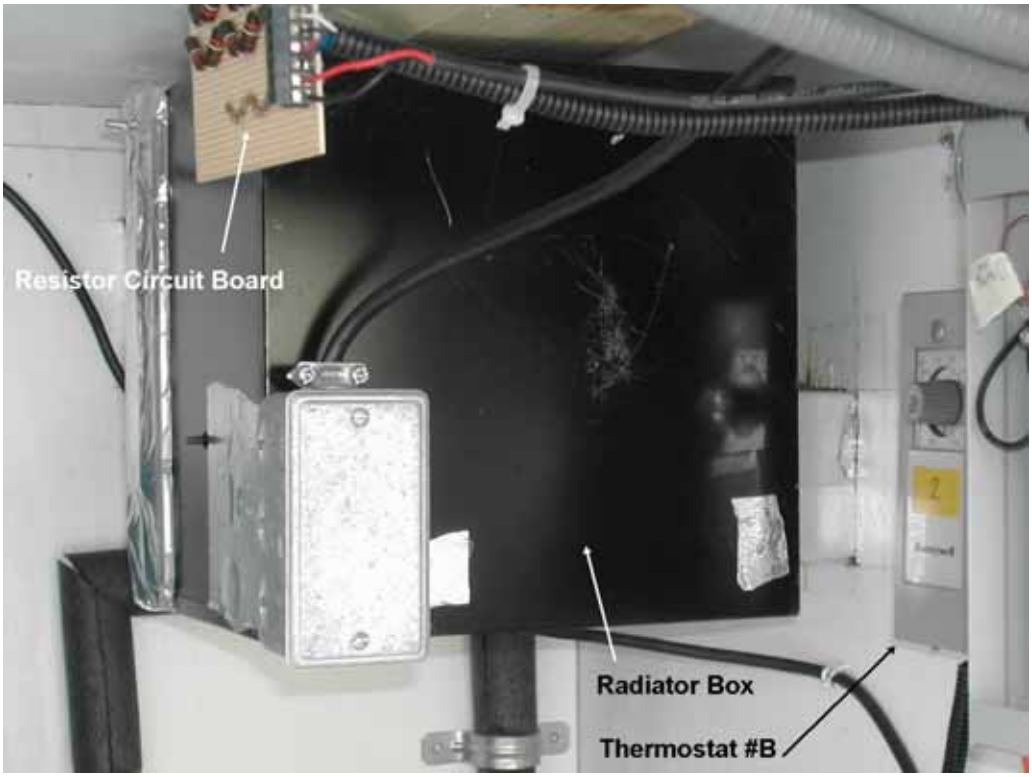


Figure 4.16 *Heat Rejection Box. The radiator is inside the rectangular black box, and contains an air blower. Thermostat# B on the right of the photo is the control thermostat for the radiator and pump# B (shown in Figure 4.14).*

4.2.2.5 The Data Acquisition System

The data logger, a Campbell Scientific 21X Micrologger, was used to monitor and store data needed from the experiments. The logger was installed on the North wall of the experiment box (See Figure 4.17). A customized steel box was used to house the logger. The original cover of the box was cut into two parts: an upper and a lower part. The upper part allowed sensors/conduits to come into the data logger box. The lower part was used to cover the logger during normal use when access to the logger was not required. Eight channels of

analog inputs were used to record data from temperature sensors, a solar radiation sensor, and the electrical power output from the PV panel (see Table 4.1).

Figure 4.17 *Data Logger: Campbell 21X Data Logger.*

4.2.3 Instrument Calibrations

The measuring devices used in the experiments include: a solar radiation sensor, temperature sensors (Type T), liquid-in-glass thermometers, and a water flow meter. These devices were calibrated before use to ensure their accuracy. These calibrations were then applied to the raw measurements to obtain more accurate measurement. The calibration methods for the instruments and calibration results are presented in Appendix C.

Table 4.1

Description of the Data Logger's Channels and Sensors Used in the Experiments

Analog Inputs Channels	Channels and Sensors Description	Locations of Sensors
1	Solar Radiation Sensor: Li-Cor (LI-200SA) Pyranometer Sensor	On the plane of PV-T^2 unit (See Figure 4.11)
2	Temperature Sensor: Thermocouple Type T for measuring temperatures of the PV panel	At the back of the PV panel in the PV-T^2 unit (See Appendix B.1)
3	Temperature Sensor: Thermocouple Type T for measuring temperatures of inlet water entering the PV-T^2 unit	Thermalwell A (See Figure 4.13)
4	Temperature Sensor: Thermocouple Type T for measuring temperatures of outlet water leaving the PV-T^2 unit	Thermalwell B (See Figure 4.13)
5	Temperature Sensor: Thermocouple Type T for measuring water temperature in the Cool Tank	Immersed in the Cool Tank at the 2 gallon level
6	Temperature Sensor: Thermocouple Type T for measuring water temperature in the Hot Tank and later was used to measure the PV panel's surface temperature for the Night Mode experiments	Immersed in the Hot Tank at the 2 gallon level. Later, moved to PV's surface
7	Voltage output from the PV panel	Resistor circuit board located on the ceiling of the box (see Figure 4.15)
8	Current output form the PV panel	Resistor circuit board located on the ceiling of the box (see Figure 4.15)

4.2.4 Test Procedures and Data Analysis

Since test procedures for hybrid PV-T systems have not been standardized, standard tests of solar thermal collectors and photovoltaic systems were used for determining the thermal and electrical performance of the Hybrid PV-T system (Huang et al., 2001; Tripanagnostopoulos et al., 2002; Zondag et al., 2002; Sandnes and Rekstad, 2002). Section 4.2.4.1 describes the standard test method used to determine the thermal performance of the hybrid PV-T^2 collector. Section 4.2.4.2 describes the standard test method used to determine the electrical performance of the hybrid PV-T^2 collector. Since one of the objectives of this research is also to test the heat rejection performance of a hybrid PV-T^2 collector, and since no previous studies

could be found that integrated a hybrid PV-T collector or used PV panels as a night sky heat rejecter, a test procedure was developed for determining the heat rejection performance of the hybrid PV-T^2 system. Section 4.2.4.3 describes the two test methods used to determine the heat rejection performance of the hybrid PV-T^2 collector.

4.2.4.1 Thermal Performance of the Hybrid PV-T^2 System

The experiment performed for this study used the PV panel as a solar thermal collector. Therefore, the PV surface, which is a sheet of glass, was considered to be similar to an unglazed flat-plate thermal solar collector
(absorber) of the hybrid PV- T^2 system. Since the proposed hybrid PV-T^2 is a liquid-type system, a relevant standard test for determining the thermal performance of the hybrid PV-T^2 collector is ANSI/ASHRAE 96-1989 (ASHRAE, 1989) Standard: Method of Testing to Determine the Thermal Performance of Unglazed Flat-plate Liquid type Solar Collector (ASHRAE, 1989). Although other standards exist for testing solar collectors, this standard was the most useful because it contained information about translating the results for use by the F-CHART analysis method.

To test the thermal performance of an unglazed flat-plate, liquid-type collector, according to the standard, the instantaneous efficiency of the collector needs to be determined at several operating temperatures. Therefore, an outside experiment, such as the one used in this study, requires experimentally measuring solar radiation incident on the PV panel, the temperature of the liquid entering and leaving the collector, the flow rate of the heat transfer fluid, the ambient temperature, and wind speed. The thermal efficiency of the unglazed flat-plate liquid-type collectors is then determined by:

$$\eta_{ther} = \frac{\dot{m} \cdot c_p (t_{f,e} - t_{f,i})}{A_g \cdot I_t} \tag{4.1}$$

where

η_{ther} = Thermal efficiency of the Hybrid PV-T^2 Collector based on gross collector area (%).

$\dot{m}$ = Mass flow rate of the heat transfer fluid (water), kg/s [lb/h].

c_p = Specific heat of the heat transfer fluid (water), J/(kg - °C) [Btu/(lb - °F)].

$t_{f,e}$ = Temperature of the heat transfer fluid leaving the collector, °C [°F].

$t_{f,i}$ = Temperature of the heat transfer fluid entering the collector, °C [°F].

A_g = Gross collector area (i.e., the PV panel's net aperture area), m^2 (ft^2).

I_t = Total solar irradiation incident upon the plane of the collector, W/m^2 [Btu/(h - ft^2)].

The test procedure and data processing used in this experiment, which is guided by ASHRAE standard 96-1989, are described below:

1. The test was performed on four clear days, which allowed four different values of the inlet temperatures to be used to obtain the values of $(t_{f,i}-t_a)/I_t$. One value of $(t_{f,i}-t_a)/I_t$ was in the negative range of approximately -0.02 to -0.15 ° (°C · m^2)/W to reduce the extrapolation error. This was accomplished by filling the tank with ice water.

2. All tests started when the sun rose and ended when the sun set. However, only four data points, two data points before and after solar noon, were used to calculated the collector thermal efficiency and $(t_{f,i}-t_a)/I_t$. The data logger's data interval time was set to 15 minutes, so the collected data is in the range of 30 minutes from solar noon.

3. The calculated thermal efficiency was then plotted on a Hottel-Whillier-Newton Plot, which has $(t_{f,i}-t_a)/I_t$ on X-axis and the thermal efficiency on Y-axis. A linear regression line of the data was generated from the four sets of data points and the equation of the regression line obtained.

4. The test intercept ($Fr\tau\alpha$) was calculated from the equation of the regression line. The test slope (FrUL) was then determined by using of the slope of the linear regression line.

4.2.4.2 Electrical Performance of the Hybrid PV-T^2 System

Four parameters were needed to analyze the Hybrid PV-T^2 system's electrical performance: 1) cell temperature at the Nominal Operating Cell Temperature (NOCT), 2) the array reference efficiency, 3) the array reference temperature, and 4) the array temperature

coefficient. The cell temperature at the NOCT and the array reference temperature were obtained from the manufacture's specifications. These two parameters are further described in detail in Appendix F.

The aim of this experiment was to analyze two electrical/thermal characteristics of the PV panel: 1) the array reference efficiency and 2) the array temperature coefficient for use with the PV F-CHART program. The array reference efficiency was obtained from the manufacture's specifications and the measurement of the physical size of the PV array. The array temperature coefficient was the rate at which the array's efficiency linearly decreased with increasing panel temperature. The array temperature coefficient was obtained from the relationship of the PV's efficiency and the PV array's temperatures. This required experimentally measuring: the solar radiation on the PV panel, the temperature of the PV panel, the ambient temperature, and the power output from the PV panel. The measured data were then used to calculate efficiency of the PV panel, which is determined by:

$$\eta_{elec} = \frac{P_{PV}}{A_g \cdot I_t} \tag{4.2}$$

where

η_{elec} = Electrical efficiency of the Hybrid PV-T Collector based on gross collector area (%).

P_{PV} = Power, electrical output, of the photovoltaic panel (PV), W.

A_g = Gross collector area (PV panel's aperture area), m^2 (ft^2).

I_t = Total solar irradiation incident upon the aperture plane of collector, W/m^2 [$Btu/(h - ft^2)$].

The test procedure to measure the parameters required to calculate the electrical efficiency and the array temperature coefficient was based upon the guidelines of two standard tests: 1) ASTM Standard E 1036 (ASTM 1996), and 2) the International Standard IEC 61724 (IEC, 1998).

ASTM Standard E 1036 describes test methods of the electrical performance of photovoltaic modules and arrays (non-concentrator terrestrial photovoltaic device) under natural or simulated sunlight using a calibrated reference cell. International Standard IEC 61724

describes general guidelines for monitoring and analysis of the electrical performance of photovoltaic systems.

The test procedure and data processing used in this research are described below:

1. The test was performed simultaneously with the experiment of thermal solar collection. Thus, the test is performed on at least four clear days.

2. The test started at sunrise and ended at sunset. However, four data points, two data points before and after solar noon, were used to calculate the PV's electrical efficiency. The data logger's data interval time was set to 15 minutes, so the collected data is in the range of 30 minutes from solar noon.

3. The calculated PV panel's efficiency was then plotted on the Y-axis against the panel's temperature on the X-axis. A linear regression line of the plotted data was generated using a spreadsheet program and the equation of the regression line was obtained. The array temperature coefficient was then calculated from the coefficients of the regression equation.

4.2.4.3 Heat Rejection Performance of the Hybrid PV-T^2 System

This research developed a test procedure to assess the heat rejection performance using the PV panel as a heat rejecter. The test procedure and data processing procedures of the heat rejection experiment used in this research are described below:

1. The test was performed on twelve clear nights. The test ran from sunset to sunrise the next day.

2. Unlike the experiments of the solar thermal collector performance and the PV electricity production, 15-minute data from the whole night were used to assess the heat rejection performance of the PV panel.

3. The measured data included temperatures of the water in the cool tank, inlet and outlet water temperatures, ambient conditions and the mass flow rate of the water. These data were used to calculate the heat rejected from the PV panel.

4. From the experimental results of heat rejected, a regression analysis was performed in order to define the relationship of the rate of heat rejected from the PV against environmental

parameters including ambient temperature, the PV's surface temperature, wind speed, and the sky temperature.

From the measured data, the heat rejected from the PV can be calculated by two methods, which are described below:

1) Calculating Heat Loss by the Water Temperature Difference in the Cool Tank

$$\Delta \dot{Q}_{rej,\Delta T_C} = \Delta Q_{rej-mea,\Delta T_C} + Q_{pump} \tag{4.3}$$

where

$\Delta \dot{Q}_{rej-mea,\Delta T_C}$ = energy change in the cool tank $= m \cdot c_p (t_{c,i} - t_{c,j})$ (Btu/ 15 mins)

Q_{pump} = energy gained from the water circulating pump (Btu/ 15 mins)

$\Delta Q_{rej,\Delta T_C}$ = total rejected heat (Btu/15 mins)

$\dot{m}$ = mass of the transfer fluid (water) in the Cool tank, kg (lb)

c_p = specific heat of the transfer fluid (water), J/(kg -°C) [Btu/(lb -°F)]

t_i = temperature of the transfer fluid in the Cool tank at time i, °C (°F)

t_j = temperature of the transfer fluid in the Cool tank at time j = i + 15 mins, °C (°F)

2) Calculating Heat Loss by the panel Inlet and Outlet Water Temperatures

$$\dot{Q}_{rej-mea,\Delta T_{ie}} = \dot{m} \cdot c_p (t_{f,i} - t_{f,e}) \tag{4.4}$$

where

$\dot{Q}_{rej,mea,\Delta T_{ie}}$ = measured rejected heat calculated by temperature difference of $t_{f,e}$ and $t_{f,i}$

$\dot{m}$ = mass flow rate of the transfer fluid (water), kg/s (lb/h)

c_p = specific heat of the transfer fluid (water), J/(kg -°C) [Btu/(lb -°F)]

$t_{f,e}$ = temperature of the transfer fluid leaving the collector/rejecter, °C (°F)

$t_{f,i}$ = temperature of the transfer fluid entering the collector/rejecter, $^{\circ}C$ ($^{\circ}F$)

Results from the experiment were then comparing with theoretical results, which are calculated by the following equations:

$$\dot{Q}_{rej,cal} = \dot{Q}_{cv} + \dot{Q}_{rad} \tag{4.5}$$

where

$\dot{Q}_{rej,cal}$ = Calculated heat loss (Btu/h)

$\dot{Q}_{cv}$ = Convective heat loss (Btu/h)

$\dot{Q}_{rad}$ = Radiative heat loss (Btu/h)

$$\dot{Q}_{cv} = h_{cv} \cdot A \cdot (T_{sur} - T_a) \tag{4.6}$$

$$h_{cv} = C\left(\frac{1}{d}\right)^{0.2}\left(\frac{1}{T_{avg}}\right)^{0.181}(\Delta T_{s-a}{}^{0.266})\sqrt{1+1.277(\text{Wind})} \tag{4.7}$$

(ASHRAE, 2001, pp. 25.15)

where

$\dot{Q}_{cv}$ = Convective heat loss (Btu/h), (Kreider and Rabl, 1994, p. 43-44)

A = Collector Area (Ft^2)

C = Constant depending on shape and heat flow condition
= 1.79 for horizontal plates, warmer than air, facing upward
= 0.89 for horizontal plates, warmer than air, facing downward
= 0.89 for horizontal plates, cooler than air, facing upward
= 1.79 for horizontal plates, cooler than air, facing downward

d = diameter for cylinder, in. For flat surfaces and large cylinders (d>24 in.), use d = 24 in.

h_{cv} = Convection surface coefficient (Btu/(h·ft^{2}·$^{\circ}$F), (ASHRAE, 2001, pp. 25.15)

$\dot{Q}_{cv}$ = Convective Heat Loss (Btu/h)

T_a = Temperature of ambient air ($^{\circ}F$)

T_{avg} = Average temperature of the air film = $(T_a + T_{sur})/2$ ($^{\circ}R$)

T_{sur} = Temperature of the collector surface ($^{\circ}$F)
ΔT_{s-a} = Surface to air temperature difference ($^{\circ}$R)
Wind = air speed (mph)

Net radiation between a horizontal flat plate and the sky is calculated by eq. 4.8. However a view factor is applied, because the PV panel is tilted. Equation 4.9 is used in the calculation instead of equation 4.8.

$$\dot{Q}_{rad} = \varepsilon \cdot A \cdot \sigma \cdot (T_{sur}^4 - T_{sky}^4) \tag{4.8}$$

$$\dot{Q}_{rad} = \varepsilon \cdot A \cdot F_{c-s} \cdot \sigma \cdot (T_{sur}^4 - T_{sky}^4) \tag{4.9}$$

$$T_{sky} = T_a \left[0.711 + 0.0056 T_{dp} + 0.000073 T_{dp}^2 + 0.013 \cos(15t)\right]^{1/4} \tag{4.10}$$

where

$\dot{Q}_{rad}$ = Radiative heat loss (W), (Duffie and Beckman, 1991, 157-158)
A = Collector Area (m^2)
t = Hour from midnight
T_a = Temperature of ambient air (K)
T_{dp} = Dew point temperature ($^{\circ}$C)
T_{sur} = Temperature of collector surface (K)
T_{sky} = Temperature of sky (K), (Berdahl and Martin, 1984)
ε = Emissivity
σ = Stefan-Boltzmann constant (5.67 x 10^{-8} W/($m^2 \cdot K^4$)
F_{c-s} = Tilt Factor or Shape Factor from the collector to sky = $\frac{1+\cos\beta}{2}$ (Martin, 1989)
β = Slope, the angle between the plane of the surface in question and the horizontal; $0^{\circ} \le \beta \le 180^{\circ}$.

4.3 Analysis of Impact of Hybrid PV-T^2 System on the Case-Study House

This research used the F-CHART and PV F-CHART programs to analyze the thermal and electricity produced by the Hybrid PV-T^2 collector system to integrate the results into the simulation of the case-study house. For the analysis of the heat rejection, a regression model was generated from the heat rejection experiment that can be used to calculate the amount of heat rejected under Bangkok weather.

The F-CHART program (Klein and Beckman, 1985) was used to assess the thermal energy produced by the Hybrid PV-T^2 for the case-study house, which is located in Thailand. The test slope (FrUL) and test intercept ($Fr\tau\alpha$) parameters, which were used in the analysis were found from the experimental results described in Section 7.3. The input parameters and results of the solar collector analysis using F-CHART are presented in Chapter VII and Appendix F.

The PV F-CHART (Klein and Beckman, 2001) program was used to analyze the electricity produced by the Hybrid PV-T^2 for the case-study house. The PV panel efficiency and temperature coefficient were the two parameters that were also determined from the experimental results. The input parameter set and results of the photovoltaic system analysis using PV F-CHART are also presented in Chapter VII and Appendix F.

Finally, the regression models of the heat rejected by the PV panel are used to assess the potential heat rejection from the PV array on the case-study house under Bangkok weather data conditions.

4.4 Building Energy Simulation

4.4.1 Creating the Base Case DOE-2 Input File

A computer model of the case-study house was constructed using the DOE-2 program (LBNL, 1999, 2001). The input file, which describes the case-study house, consists of many components as shown in Figure 4.18. The building dimensions were obtained from the architectural drawings of the case-study house. The DrawBDL architectural rendering program, (Huang and Associates, 2000), was used to check the accuracy of the building's geometry in the DOE-2 input file. A cardboard model was also used to study the case-study house's interior spaces and their relationship (see Figure 4.19), which was especially helpful for determining

how to zone the house. A virtual model was also constructed using AutoCAD (a computer-aided design program) in order to help construct the case-study house model in the DOE-2 program. Figure 4.20 shows the virtual model built using AutoCAD. All coordinates of the walls, windows, and roofs were retrieved from the virtual model, and input into the DOE-2 program. After the initial DOE-2 input file was constructed and the first run was performed, the model was calibrated to compare the measured and simulated thermal conditions in the spaces and the energy use. Section 4.4.2 describe methods used to calibrate the model.

The simulation of the case-study house, which is located in the vicinity of Bangkok, Thailand, uses the Bangkok 2000 weather data. The Bangkok weather data was obtained from the Meteorological Department of Thailand. The weather data, which consisted of computer files in ASCII text format, were directly obtained on diskettes. Next, the weather data was reformatted so it could be processed by the DOE-2 program. To accomplish this, the Bangkok 2000 weather data was reformatted into the Test Reference Year (TRY) data format. Preparation and generation of the DOE-2 weather file is discussed in Appendix E.

4.4.2 Calibrated Simulated Model to the Case-Study House

For this study, two comparisons were used for the calibration:

1) Average monthly electricity use. This was a comparison between the actual monthly electricity used from the electricity bills and the monthly electricity use from the DOE-2 simulation.

2) Hourly zone temperatures. Measured temperatures in the unconditioned spaces and the air-conditioned spaces of the case-study house were compared with the simulated model's zone temperatures.

Additional details about the calibration of the simulation are presented in Chapter VII. The statistical methods used to calibrate the model are also presented.

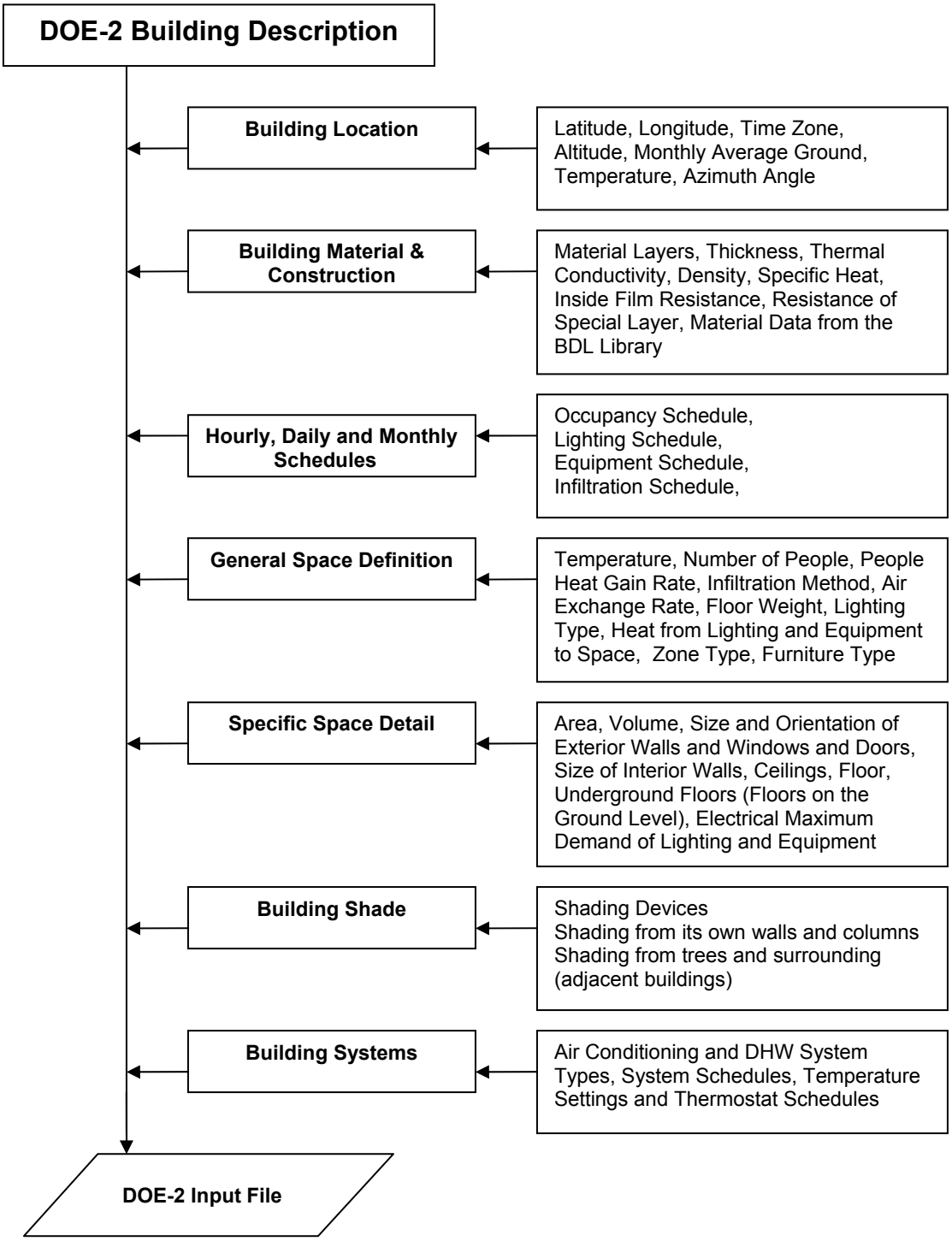


Figure 4.18 *Diagram of the DOE-2 Input File for the Case-Study House.*

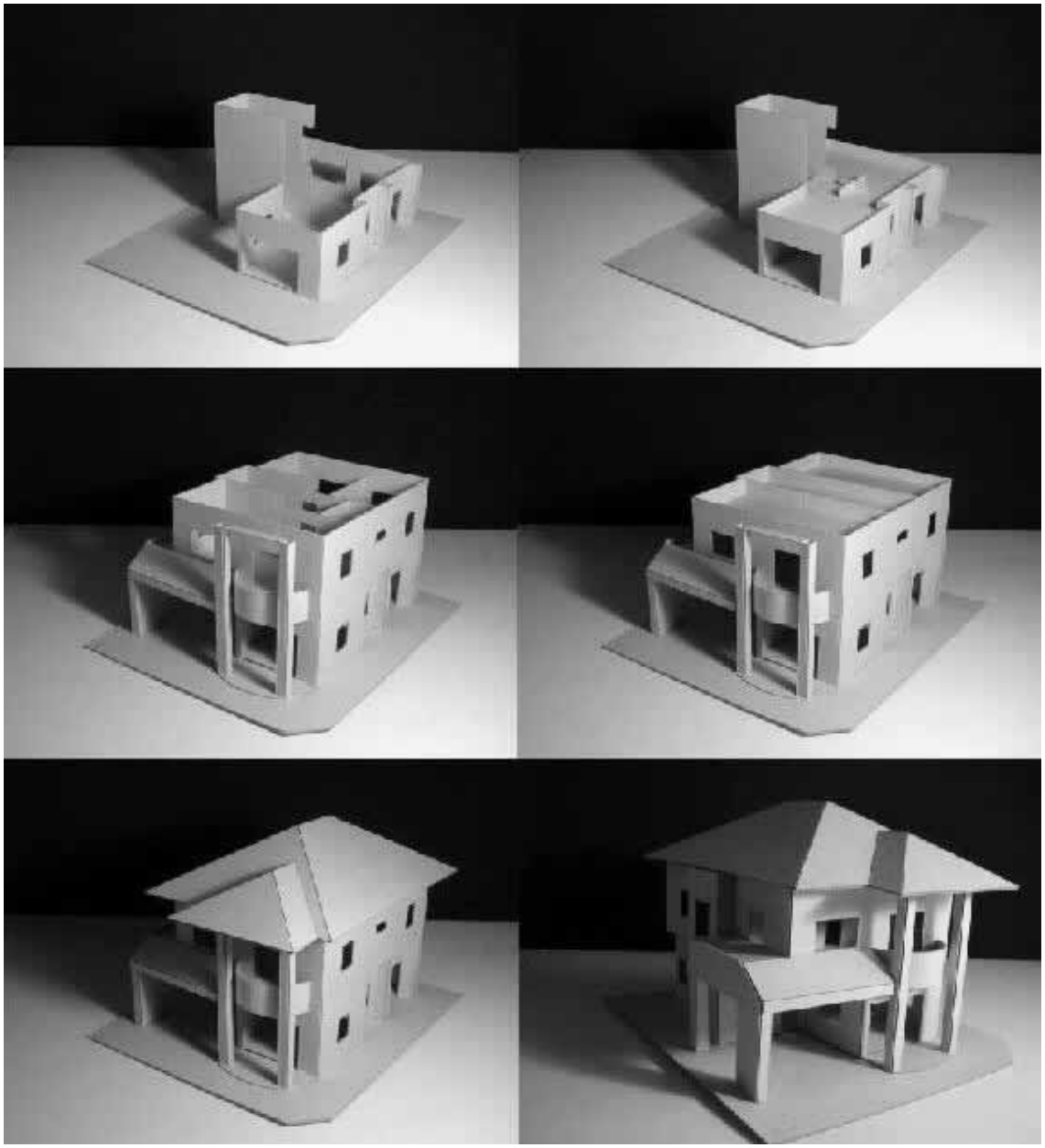
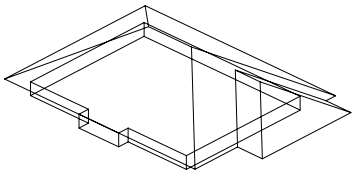
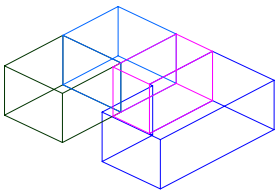


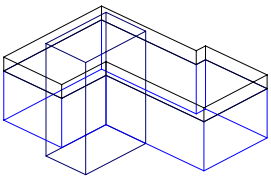
Figure 4.19 *Cardboard Model of the Case-Study House. The model could be disassembled to help see the relationships of the spaces on each floor, and the interior walls and floors between the first and second floor.*



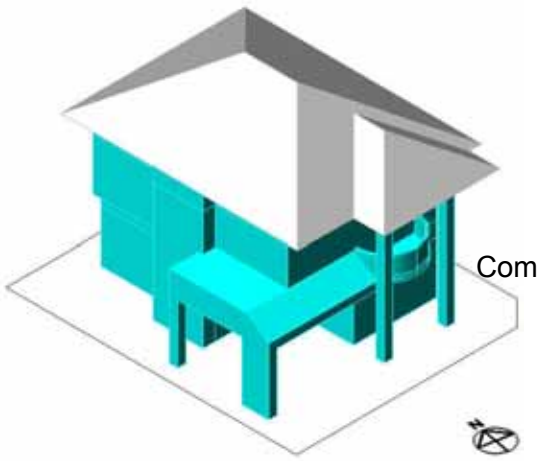
Attic



Second Floor



First Floor



Complete Model

Figure 4.20 *Virtual Model of the Case-Study House.*

4.5 Economic Analysis

An economic analysis of the case-study house that compares the base-case building with the same building improved by the energy efficiency strategies and renewable energy technologies was performed using the annualized life-cycle cost analysis method that was described in ASHRAE (1999) and Haberl (1993). Details of equations used in the analysis are presented in Appendix G.

The primary input data for the economic analysis includes the owning costs, operating cost, and maintenance costs. Other elements that were established or defined to calculate annual owning costs, include: study period length, discount rate (id), inflation rate (j), mortgage rate (im), and periodic costs such as insurance, and property tax. The final results of the economic analysis, which were annualized life-cycle costs and monthly payments, were used to determine which energy efficiency strategies or renewable energy technologies were acceptable to consumers.

4.6 Summary of the Methodology

This chapter described the research methods that were used to develop a calibrated simulation of the case-study house, the experiments of a hybrid PV-T^2 collector system, the analysis of the impact of the hybrid PV-T^2 system on the case-study house, the thermal building simulation, and the economic analysis.

The analysis of the case-study house involved the selection of the case-study house, data collection, and instrument calibration. Selection of the case-study house had three criteria: 1) the preferred location was in the metropolitan Bangkok area or its vicinity, 2) the selected house represented a typical contemporary detached Thai house, and 3) the preferred number of occupants was three to four persons. The data collection of the case-study house included the building information, the building's energy use, and climate data. The case-study house was surveyed and its monthly utility bills were obtained. Portable data loggers were installed in the case-study house to measure and record the temperature and humidity conditions in the case-study house. Weather data for the corresponding region were also obtained to facilitate the calibrated simulation.

The experimented measurements of the hybrid PV-T^2 collector system included the design of the experiments (day mode and night mode), design and construction of the experimental box, instrument calibration, and the development of test procedures and data

analysis. The hybrid PV-T^2 collector system was designed to measure the thermal and electricity performance during the daytime and to measure the heat rejected during the nighttime. The experiments were performed on the roof of Langford Architecture Building A at Texas A&M University. Instrument calibration was performed on the solar radiation sensor, temperature sensors (thermocouples), and flow meter prior to the initiation of the experiment.

The test procedures and data analysis of the thermal, electrical, and heat rejection performance of the hybrid PV-T^2 collector system were described. The test procedures and data analysis of the system's thermal performance were developed based on standard: methods. The test procedures and data analysis of the system's electrical performance was developed based upon two standards. For the heat rejection experiment, a procedure was developed that would collect data over a range of temperatures to allow for an empirical validation of previously published equation.

For the analysis of the impact of the hybrid PV-T^2 collector system on the case-study house, the F-CHART and PV F-CHART programs were used to analyze the thermal and electricity energy produced by the hybrid PV-T^2 collector system that was then integrated onto the case-study house. For the analysis of the heat rejection, regression models were generated from the heat rejection experiments that can be used to calculate the amount of heat rejected under Bangkok weather conditions.

For the building thermal simulation, the DOE-2 program (LBNL, 1982) was used to analyze various building improvements. A Test Reference Year (TRY) of weather data for Bangkok, 2000, was generated using measured Bangkok weather data. The preparation and generation of the DOE-2 weather file is discussed in Appendix E.

The economic analysis of the case-study house that compares the base-case building with the same building improved by the energy efficiency strategies and renewable energy technologies was performed using the annualized life-cycle cost analysis method (ASHRAE, 1999; Haberl, 1993).

CHAPTER V

DATA ANALYSIS AND RESULTS OF THE CASE-STUDY HOUSE

This chapter discusses the case-study house, including the measured thermal conditions of the spaces in the house, and the building's energy consumption compared to other Thai residential units. An analysis of the thermal conditions of the spaces compared to outdoor conditions is also presented.

5.1 The Case-Study House

A typical contemporary single-family detached Thai house was selected as the case-study house for this research. The case-study house met the three primary selection criteria, which are the location, building characteristics, and number of occupants, as discussed in Chapter IV, Section 4.4.1. The case-study house is located in a municipal area of Nonthabury province which is in the vicinity of metropolitan Bangkok. The house was visited and surveyed in May of 2000. The building's exterior and interior spaces were photographed, and the building's construction and materials were also inspected. Portable data loggers were installed in both the conditioned and unconditioned spaces as described in the research methodology in Chapter IV. This chapter presents the details of the case-study house including the building and occupant characteristics, the building's air conditioning systems, drawings of the house and pictures of the interior and exterior spaces.

5.1.1 Building Characteristics and Occupants

The case-study house is a three bedroom, two-story building with a hipped roof (see Figure 5.1). The structure of the house is post and beam reinforced concrete. The first floor is reinforced concrete slab on ground. The second floor is reinforced concrete floor on concrete beams. The exterior and interior walls of the house are four-inch brick with painted cement plaster. All of the windows and exterior doors are wooden-framed, single-pane glass. The roof structure is steel frame which is covered with cement tiles. The roof is not insulated. However, the second floor ceilings are insulated with four-inch fiberglass wool coated with a reflective layer (see Figure 5.2). It can be seen in Figure 5.2 that the surface of the reflective layer was covered with dust, which diminishes the effectiveness of the reflective layer of the insulation.

Figure 5.1 *The Case-Study House. The picture shows the southeast view of case-study house, which is situated on a corner lot. The street on the left is the main street of the neighborhood. The street on the right is a dead-end street, which serves only 2 houses. The back of the house is next to an undeveloped open-space area. Thus, the house has only one side (west side) that is shaded by an adjacent house. This picture also shows the only green vegetation around the house which is on the east side.*

The occupants of the selected case-study house include three adults and a three-year old child. One of the adults is a college student who stays at the house only on weekends. Therefore, the house was assumed to be occupied by two adults and one child on the weekdays, with three adults and one child on the weekends. This compares well with the average Thai household size, which is 3.6 persons (NSO 2000).

The house faces south and is situated on a corner lot (as shown in Figure 5.1). The lot size is relatively large when compared to the neighboring houses. The extra land allows space for plants, which are located on the east side of the house (see Figures 5.1 and 5.3). These think mongo plants provide natural good shading on the living room and the master bedroom.

Figure 5.2 *Inside the Attic. This picture shows the structure of the roof and the insulating material of the second floor ceiling. The roof's steel frame is supported by concrete columns. 240 Volt branch circuit wiring is draped in the foreground. The vertical lines are the ceiling's hangers. This picture was taken over the second floor bathroom's ceiling facing north.*

5.1.2 The Building's Air Conditioning Systems

The case-study house is partially air conditioned with two packaged air conditioning systems: one in the master bedroom and the other in bedroom-2. Both air conditioning systems are mini-split systems that have air-handling units in the rooms and condensing units outside (see Figures 5.4 and 5.5). The master bedroom's air conditioning system has a cooling capacity of 17400 Btu/hr (1.45 tons or 5.1 kW). Bedroom-2's air conditioning system has a cooling capacity of 12,000 Btu/hr (1.0 tons or 3.5 kW).

Figure 5.3 *Green Area of the House. This picture shows the lawn area of the house on the east side. The picture was taken under a pergola that provides shading for the dining room. The big tree is a mango plant that is covered with large opaque leafs. It also provides shading for the building including the master bedroom that is on the second floor.*

Figure 5.4 *Air-handling Unit of the Master Bedroom. Above the window on the right wall (west facing wall) is the air-handling unit of the air conditioning system of the master bedroom. The condensing unit is located outside on the right wall. The thermostat (not seen in the picture) is on the interior wall that separates between the master bedroom and the hallway.*

Figure 5.5 *Condensing Unit of Bedroom-2's Air Conditioning System. This picture shows the north facing wall of the second floor, which are bedroom 2 (on the left) and bedroom 3 (on the right). On the left of the picture is the condensing unit of the mini-split air conditioning system that serves bedroom-2. This air conditioning system is normally operated only on weekends. Bedroom 3, which is on the lower right of the picture, is not air-conditioned. Hence, the windows are full open.*

5.1.3 Building Drawings and Pictures

5.1.3.1 The Building's Site Plan

The house is in a village that was developed in a suburban area of metropolitan Bangkok. However, the lot sizes of the houses in the village are quite small, due to the high cost of the land. The land area of the case-study house is about 1,940 sq.ft., while the building foot print is about 870 sq.ft. with a total area of 1,641 sq.ft. Thus, the ratio of the land to building area is about 1.2 : 1. The site plan of the case-study house is shown in Figure 5.6.

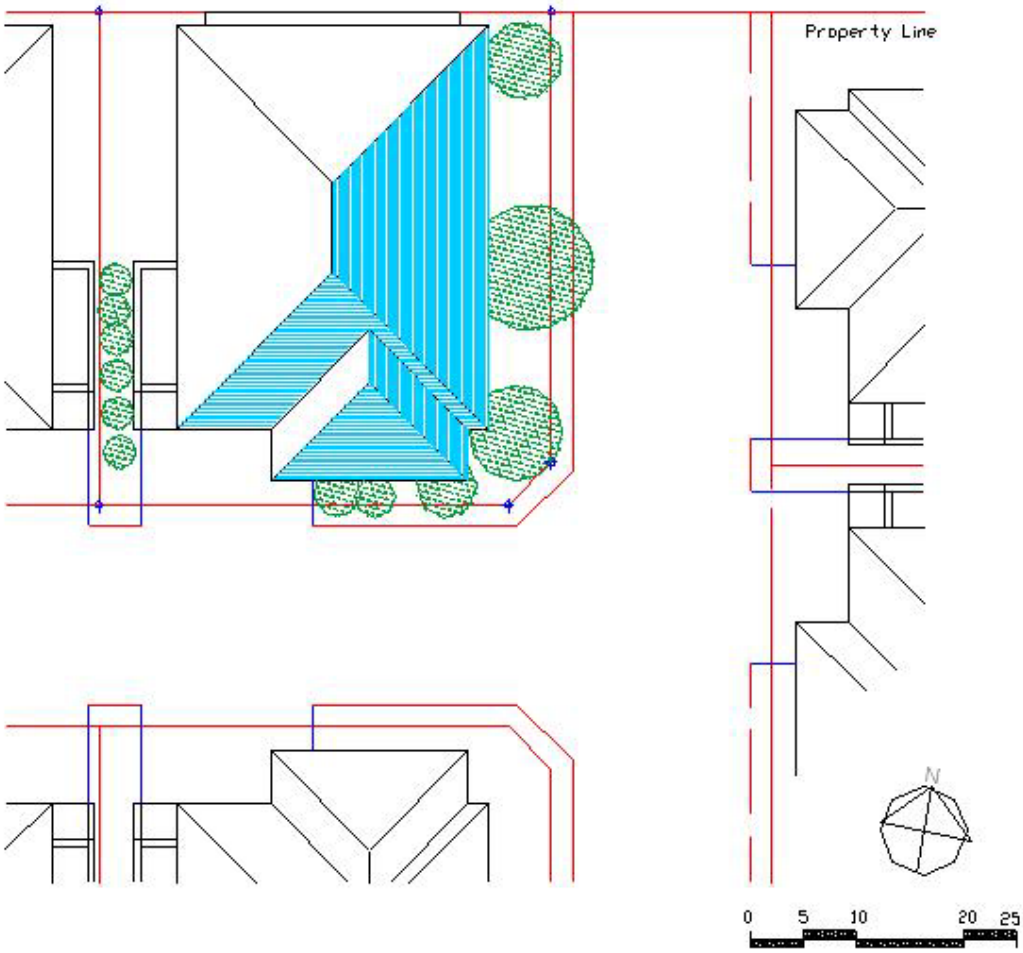


Figure 5.6 *Site Plan. The house is facing almost directly south. It has only one side, which is on the west that is adjacent to a neighbor. The east side faces a dead-end street. On the north, it is next to an undeveloped open space.*

5.1.3.2 Building Floor Plans and Pictures

Figure 5.7 shows the first floor plans of the case-study house. The interior spaces on the first floor are the living room, dining room, kitchen and bathroom. The garage is a semi-interior space, which has no external walls on the west and south sides, due to the presence of the driveway. There is also a courtyard on the northwest of the building. The function of the courtyard is for activities such as clothes drying. All of the spaces in the first floor are unair-

conditioned. Therefore, the thermal conditions of the first floor spaces rely on controlling the fenestration which consists of opening and closing the windows, doors and curtains to cool the space with natural ventilation.

Figure 5.8 shows the second floor plan of the case-study house. The spaces on the second floor are the master bedroom, bedroom-2, bedroom-3, a bathroom, the stairway and hall. The master bedroom and bedroom-2 are the only two spaces on the second floor (and also of the house) that are air-conditioned. These two spaces are conditioned by two separate thermostatically controlled air conditioning systems, which are only used in the nighttime. Bedroom-2 is not used on the weekdays, so the air conditioning system in this room is operated only on weekends. Bedroom-3 is used as a multipurpose room, for such activities as clothes ironing, and includes space for furniture storage, and book shelves. The bathroom on the second floor is the only space in the house that has an electric water heater, since it is the only bathroom that the residents used for bathing or showering; the bathroom on the first floor is not used for bathing.

Figure 5.9 shows the courtyard on the northwest of the building. The courtyard is used primarily for clothes drying as seen in the picture. The courtyard is adjacent to the neighboring building on the west side (left side of the photo). In the courtyard, there is a 1,600 liter water storage tank with a water pump located next to the building (see Figure 5.10). This tank serves as a main water storage for the house's water supply needs. The water pump is necessary because of the low water pressure from the municipal water supply system.

The living-dining room is shown in Figure 5.11. This space is not air-conditioned, so natural ventilation is maximized by the opening of windows and doors. Figure 5.12 is a view looking from the dining area to the kitchen. A 14-cu.ft. three-door refrigerator is on the left of the picture. The size of the refrigerator is large compared to that of a typical Thai household. More than 70 percent of refrigerator sales in Thailand are one-door manual-defrost models. Approximately 15 percent are two-door automatic defrost models (EPPO, 2001). Large residential refrigerators, such as the one in this household, therefore represent less than 15 percent of the total residential sales in Thailand (EPPO, 2001).

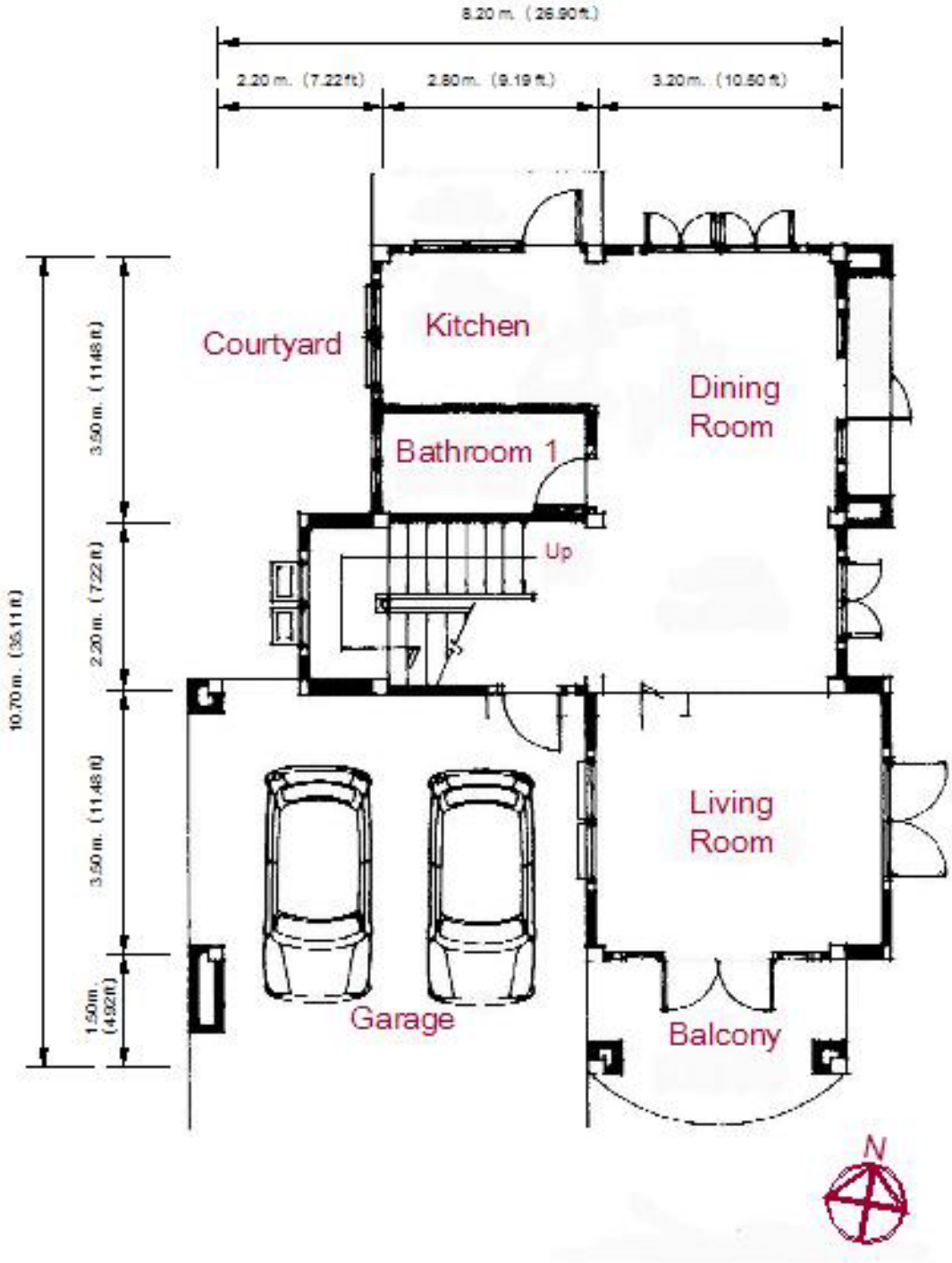


Figure 5.7 *First Floor Plan.*

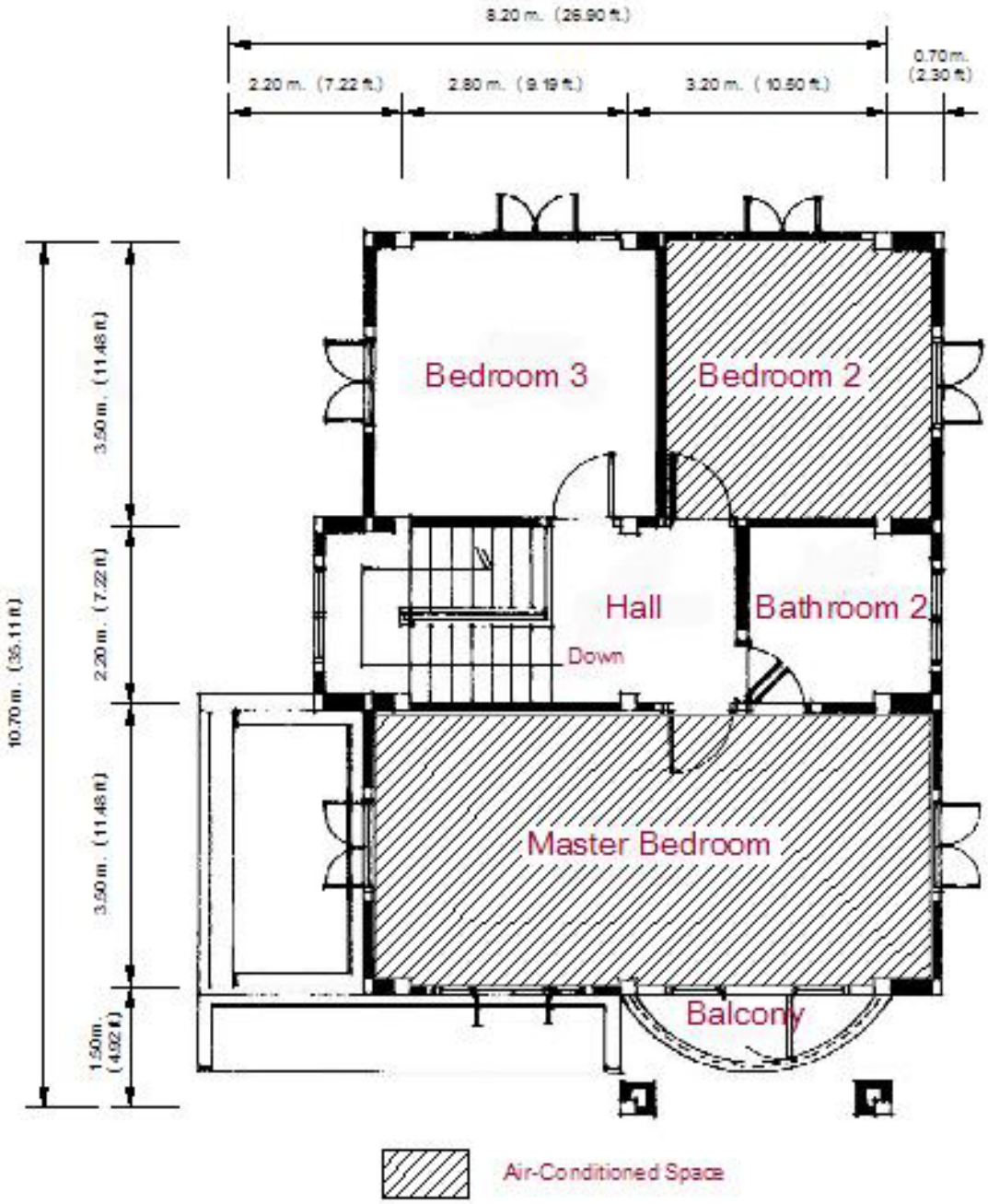


Figure 5.8 *Second Floor Plan.*

Figure 5.13 shows bedroom-3, which is an unconditioned space located on the second floor. This space is not used as a bedroom, but rather it serves as a multipurpose space as seen in the picture. On the right side of Figure 5.13, a second refrigerator is located in the hallway. This refrigerator is used to refrigerate drinking water, medicine, and milk for a baby. Having more than one refrigerator is not typical for Thai households, therefore the energy used for refrigeration in this house is higher than an average household.

Figure 5.9 *Courtyard on the Northwest. This exterior space is primarily used for clothes drying as shown in the picture. On the right of the picture is a 1,600 liter (423 gallon) portable water tank. See Figure 5.10 for more details.*

Figure 5.10 *Water Storage Tank. This tank contains potable water from the municipal domestic water supply.*

Figure 5.11 *Living-Dining Room. The living-dining room area is an unconditioned space.*

Figure 5.12 *Kitchen. The kitchen is next to the dining area*

Figure 5.13 *Bedroom-3: An Unconditioned Space on the Second Floor. The left side of the picture is the view from the hallway looking toward the exterior. The right part of the figure is the view from inside the room toward the hallway of the second floor. Bedroom 3 is actually used as a multipurpose room, (i.e., clothes ironing and storage of books and furniture).*

5.2 Analysis of the Measured Data and Thermal Comfort

As mentioned earlier in Section 5.1.2, the case-study house was partially air-conditioned, so it had conditioned spaces and unconditioned spaces. Thus, measurements of thermal conditions in the case-study house were performed in both types of spaces for the purpose of comparing the measured temperatures with simulated temperatures. To accomplish this, portable data loggers (Onset Computer Corporation, 2000) were installed in the case-study house from June to December 2000. The placement of the data loggers was described in Chapter IV. Time-series plots of the seven months of measured data for all spaces are included in Appendix A. This section presents results of the analysis of the measured data: temperatures and humidity.

5.2.1 Measured Temperatures in Spaces of the Case-Study House

Figure 5.14 shows the distribution of the indoor dry bulb temperatures (i.e., living room, master bedroom, bedroom-3, and attic) compared to the coincident outdoor ambient temperatures. To accomplish this Bangkok weather data for the year 2000 was obtained from the Department of Meteorology, Thailand.

As mentioned previously, the living room, bedroom-3 and attic are all unconditioned spaces. However, these spaces are on different floor and orientations of the building. Therefore, they show slightly temperature distributions. The living room is on the first floor and has exterior walls in almost every direction (i.e., south, east and west). Bedroom-3 is on the second floor and has only two exterior walls; west and north walls. However, bedroom-3 is also under the attic.

From Figure 5.14, the outdoor temperatures cover a wider range than those of the indoor spaces except the attic. The range of outdoor temperatures (highest temperature – lowest temperature) is 32 °F; while the indoor temperatures of the unconditioned living space are in narrower ranges (17 °F and 21.5 °F for living room and bedroom-3, respectively). The outdoor temperatures, however, have only slightly dominant temperatures in the 79-82 °F range, while the indoor temperatures of the living room and bedroom-3 have dominant temperatures in different ranges. The measured temperatures that occurred most often in the living room and bedroom-3 were 83-86 °F and 85-88 °F respectively, indicating that bedroom-3, which was on the second floor, was hotter than the living room. However, the frequency of the 85-86 °F

dominant temperature of the living room was larger than that of bedroom-3. For the attic, temperature conditions varied over a much wider range than those outdoors, especially at higher temperatures. The attic temperatures reached the maximum temperature range of 115-116 °F, while the highest outdoor temperatures are in the range of 95-96 °F.

For the conditioned space, the master bedroom had a range of temperatures very close to those of bedroom-3 which is also on the second floor. However, the most frequent temperatures in the master bedroom are in the range of 79 to 82 °F, which is lower than those of bedroom-3 (85-88 °F). This difference is certainly because of the operation of the master bedroom's air conditioning system during the evening. The most frequent temperature range of the master bedroom accounted for approximately one half of the total hours of the measured data (2600 hours of temperatures in the range of 79 to 82 °F to the total of 5136 hours). This confirms that the master bedroom's air conditioning system was operated about 12 hours per day as scheduled. In general, the indoor temperatures (except in the attic) have less variability than the outdoor temperatures.

The 24-hour daily temperature profiles of the indoor spaces in the case-study house are shown in Figure 5.15. The daily temperature profiles of the living room and bedroom-3 show similar 24-hour profiles (i.e., the temperature swings). In both spaces, the temperatures reach the lowest point in the morning about 7:00 to 8:00 a.m., and reach the highest point in the afternoon (at about 3:00 p.m. for the living room and about 4:00 p.m. for bedroom-3). The difference in the range of hourly temperatures of both spaces seems to suggest the influence of the ground temperature. The location of the space also plays a crucial role in the temperatures profiles.

In reference to the ASHRAE Comfort Zone, the mean temperatures of the living room and bedroom-3 rarely dropped into the upper limit of the comfort zone. Whereas, in the master bedroom the mean temperatures approached the upper limit soon after the A/C was switched on and remained there until the A/C was switched-off. Interesting, the ambient temperatures reached the upper limit of the ASHRAE comfort zone about the same time as the master bedroom.

The daily temperature profile of the attic shows an obvious difference between temperature conditions in the daytime versus the nighttime. The attic's mean temperature reaches its lowest point of about 78 °F in the morning (about 7:00 a.m.), and rises rapidly to the reach highest point of about 102 °F at about 1:00 to 2:00 p.m. The temperature declines after

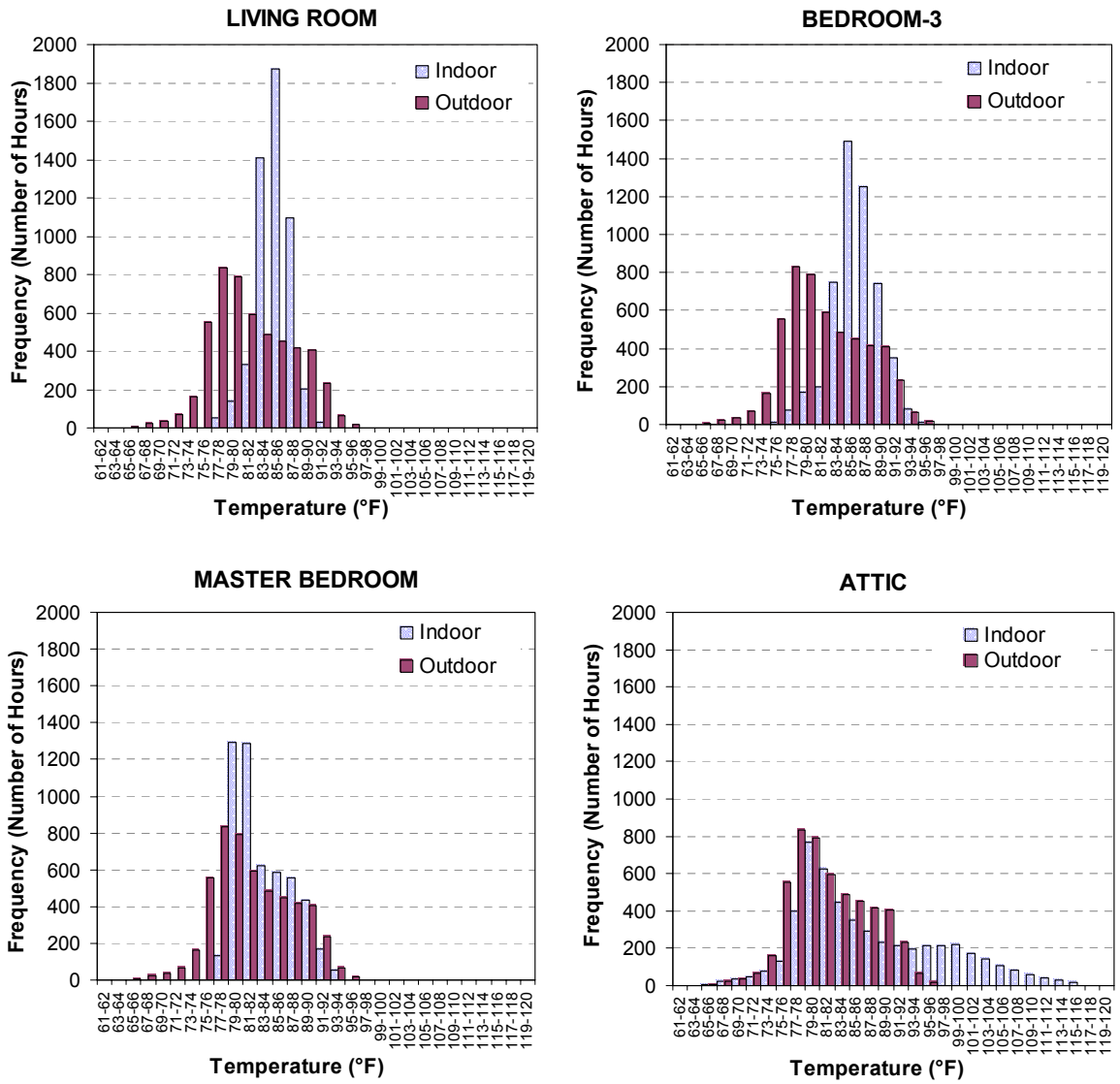


Figure 5.14 *Histograms of Measured Temperature Conditions in the Case-Study House (June – December 2000).*

2:00 p.m., but is still relatively high in the afternoon and the evening compared to the outdoor mean temperatures. The mean temperatures of the attic from 3:00 p.m. to 6:00 p.m. were between 90 °F to 100 °F, while the outdoor mean temperature in the same period were between about 82°F to 88 °F. After 6:00 p.m. the attic's temperatures were still higher than the outdoor

temperatures. In the early morning hours between 1:00 to 8:00 a.m. the mean attic temperatures are virtually identical to the ambient temperatures, which show the influence of the attic ventilation and night-sky radiation. The peak of the attic's temperature profile in the daytime (at 2:00 p.m.) shows that solar radiation plays a very significant role in the temperature of the attic. The relatively high temperatures of the attic after sunset show the impact of the high thermal mass roof and attic walls, which are the main components of the roof.

The daily temperature profile of the master bedroom is the only profile of an air-conditioned space (Figure 5.15). According to the air conditioning operating schedule obtained from the residents, the air conditioning system of the master bedroom was operated only during nighttime (from 7:00 p.m. to 7:00 a.m.). The set-point temperature of the thermostat was 26 °C (78.8 °F). In Figure 5.15 the profile shows a relatively flat profile during the air-conditioned period. The measure data show that it takes, on average, about two hours to lower the bedroom temperature to the thermostat set-point. The mean temperature once the room temperature is pulled-down is about 81°F, which is slightly higher than the thermostat set-point. This may be caused by the placement of the data logger. The data logger was placed on an interior wall that was partitioned between the master bedroom and the hall, which is an unconditioned space on the second floor. There were no data loggers placed in the hall. However, the hall is adjacent to bedroom-3, which is also not air-conditioned. Therefore, simulated temperatures in the hall, during the master bedroom's conditioned period, were assumed to be a little higher than the temperatures in bedroom-3, since there is a refrigerator in the hall. The mean temperatures of bedroom-3 varied from approximately 84 °F to 87 °F during the period that the master bedroom was conditioned (from 7:00 p.m. to 7:00 a.m.). Thus, there were temperature differences of about 5 to 9 °F between the conditioned and unconditioned spaces. This was believed to be the reason for the consistently higher logger readings.

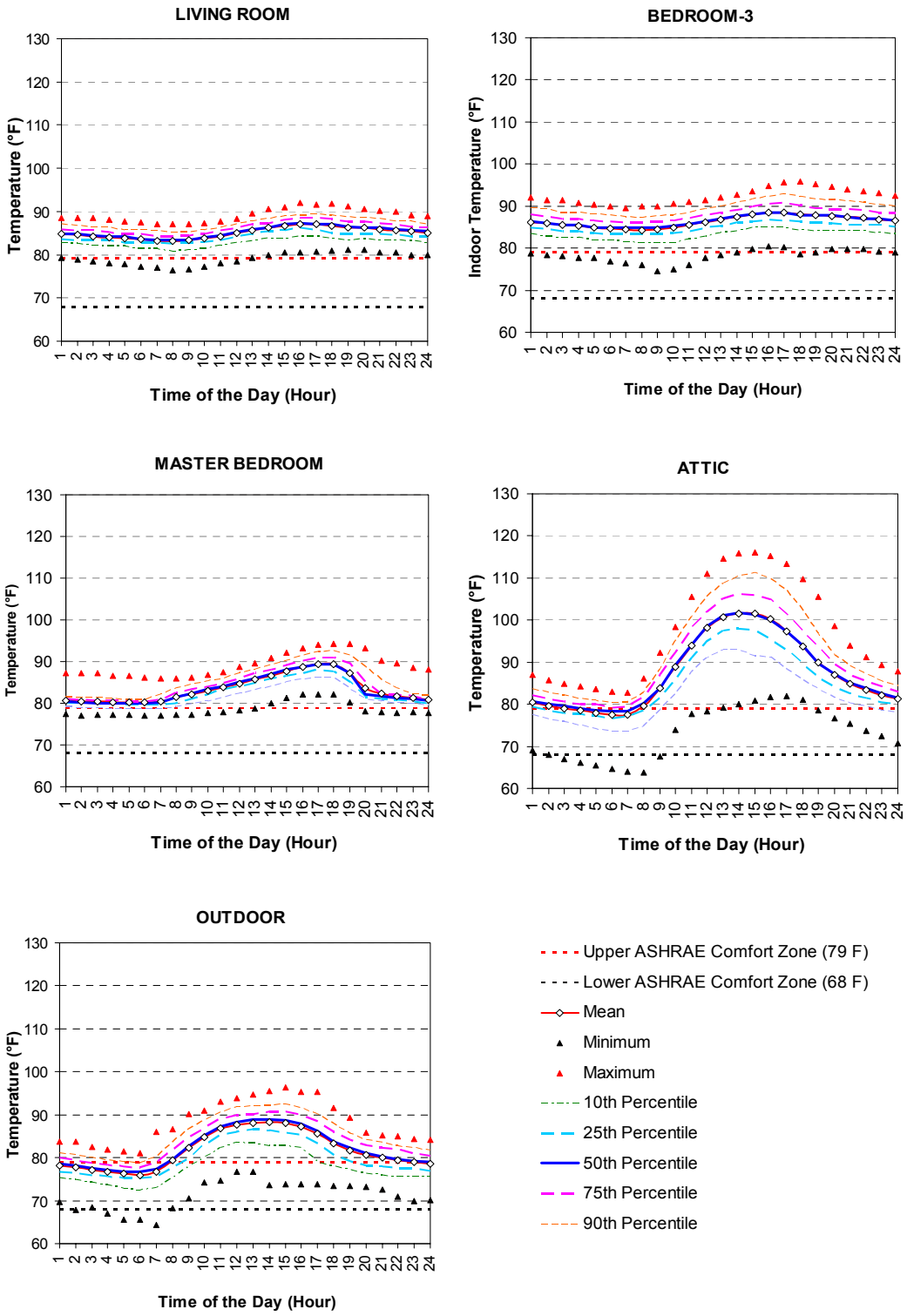


Figure 5.15 *Daily Temperature Profiles in the Case-Study House (June – December 2000).*

5.2.2 Measured Humidity in Spaces of the Case-Study House

Figure 5.16 shows the variability of the relative humidity of the indoor spaces (i.e., living room, master bedroom, and bedroom-3) compared to outdoor relative humidity levels. The outdoor relative humidity is from Bangkok weather data for 2000 obtained from the

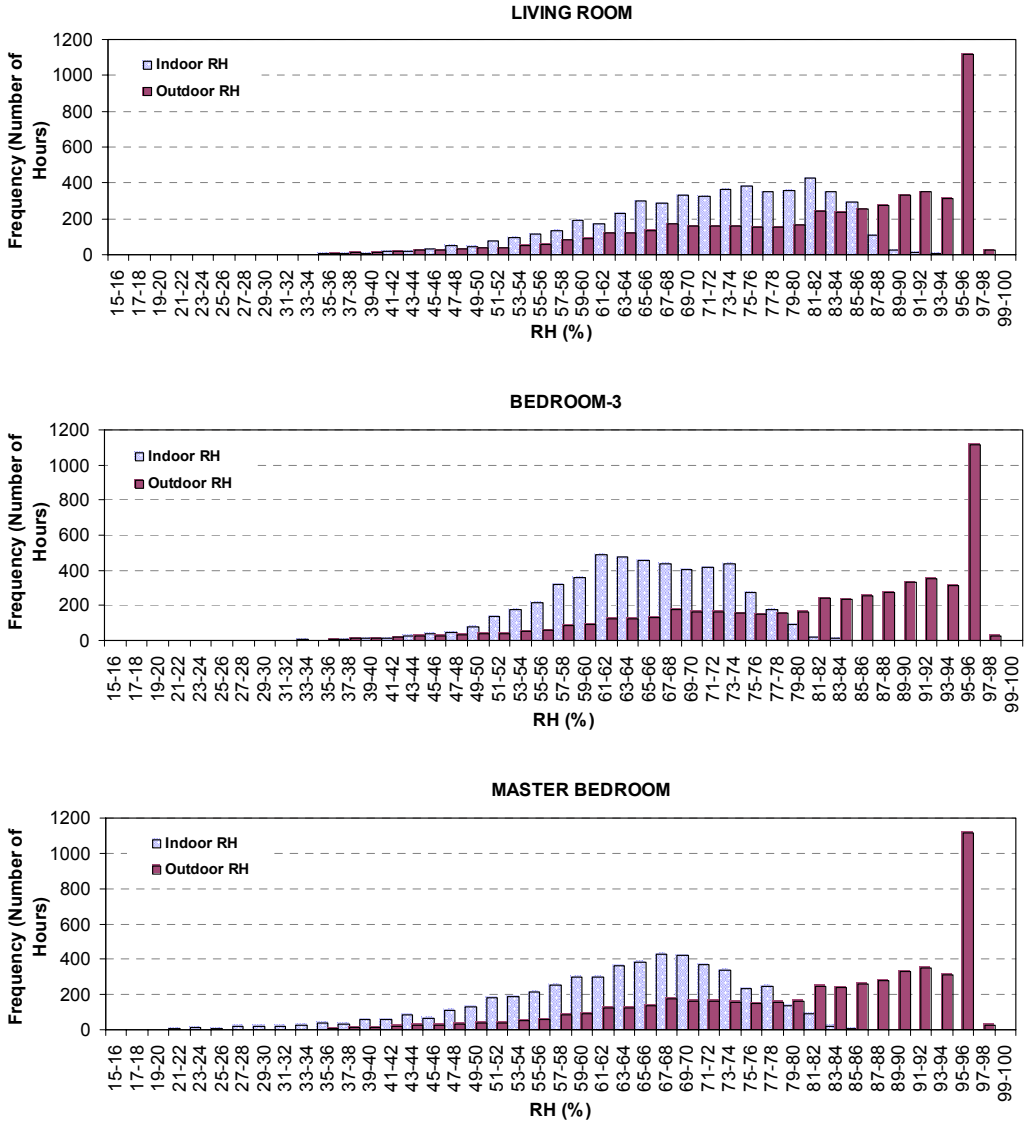


Figure 5.16 *Histograms of Measured Relative Humidity Conditions in the Case-Study House's Spaces (June – December 2000).*

Department of Meteorology, Thailand. In general, the range of relative humidity in the indoor spaces is narrower than the outdoor relative humidity. The outdoor relative humidity is in a broader range, and it has over 1,100 hours at extreme humid conditions above 95-96 % RH. The missing data above 95-96 % RH were trimmed by the Department of Meteorology. As seen from Figure 5.16, for all space, there are significant differences between the indoor and outdoor relative humidity. However, there are fewer differences when one compares their humidity levels as specific humidity.

Specific humidity is the ratio of the mass of water vapor to the total mass of the moist air (ASHRAE, 2001, p. 6.12). Figure 5.17 shows the variability of the specific humidity of the indoor spaces compared to outdoor specific humidity levels. From Figure 5.17, for specific humidity of the unconditioned spaces (i.e. living room and bedroom-3) is relatively close to the outdoor specific humidity. It could be noted that the specific humidity of living room, which is on the ground floor, is very similar to that of the outdoor. However, the specific humidity of the master bedroom, which is a conditioned space in the nighttime, is significantly different from the outdoor specific humidity. There are less hours of high specific humidity (0.018 to 0.022) of the indoor than the outdoor specific humidity. Indoor specific humidity is mostly in the lower range, which is significantly different from the outdoor. Thus, it means that most of the time, in the living room and bedroom-3 the indoor air has slightly less moisture vapor (or relative dryer) than the outdoor air. In the master bedroom this trend is more pronounced. This is because of the operation of the air conditioning system. From Figure 5.17, it can be concluded that the A/C system in the master bedroom dehumidifies the bedroom when operating, and this dry air then spills into the other spaces and partially dehumidifies the remaining rooms.

The measured indoor relative humidity, together with the measured indoor temperatures, were used to study the thermal comfort conditions of the indoor spaces. The next section presents the results of an analysis of the thermal comfort conditions in the indoor and outdoor spaces compared to ASHRAE's thermal comfort standard.

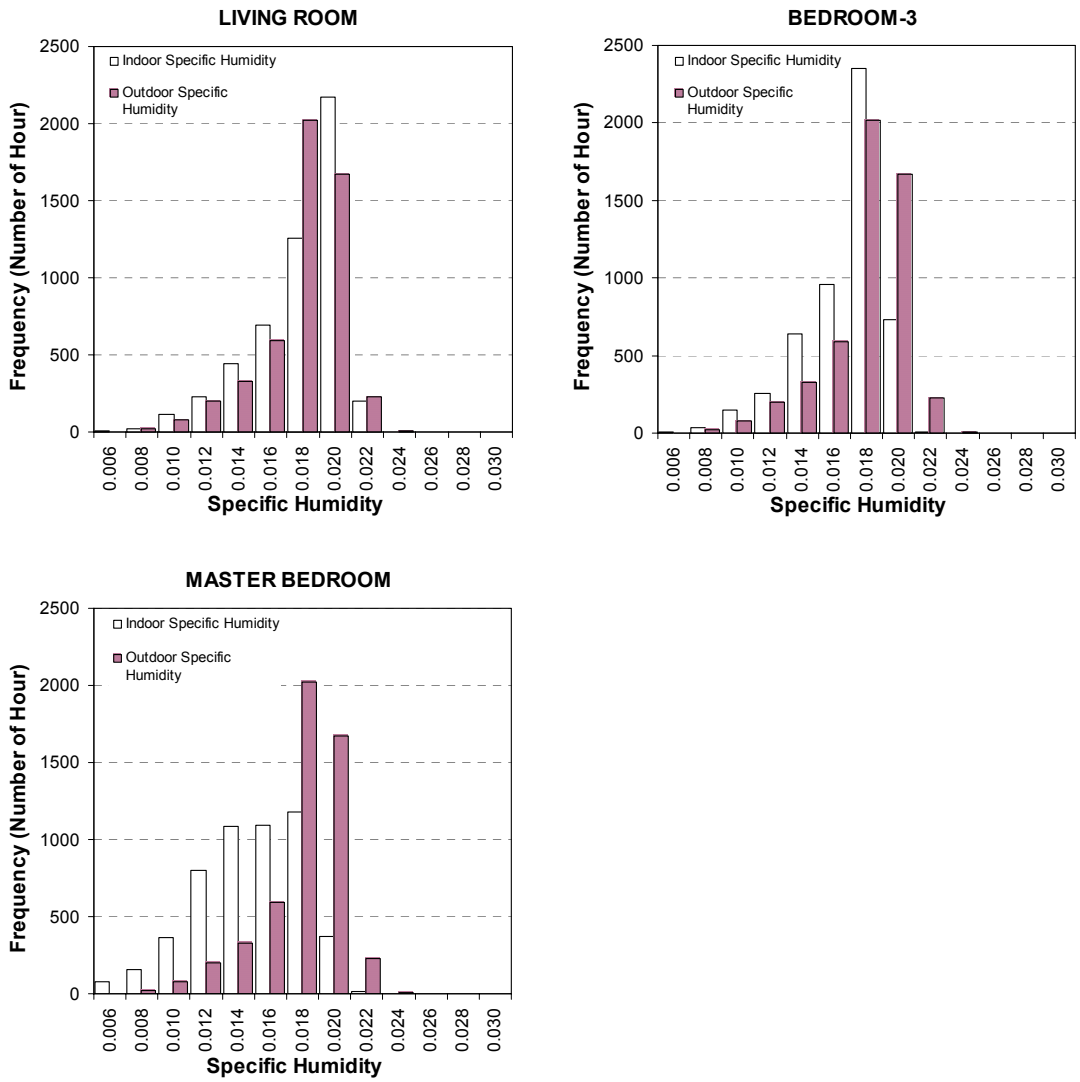


Figure 5.17 *Histograms of Measured Specific Humidity Conditions in the Case-Study House (June – December 2000).*

5.2.3 Psychrometric Plots of Measured Indoor Conditions of Spaces in the Case-Study House

Figure 5.18 shows the thermal conditions of the living room, bedroom-3, master bedroom, and the outdoors plotted on the ASHRAE psychrometric chart with the comfort zones super-imposed on the chart. As mentioned previously, the living room and bedroom-3 were

unconditioned spaces, therefore the thermal conditions in these two spaces are mostly outside ASHRAE's comfort zone. According to ASHRAE's thermal comfort standard, the occupants in the living room and bedroom-3 should not be thermally comfortable. However, it is clear that the house's occupants experienced some degree of satisfaction in these unconditioned spaces. This is probably due to the Thailand lifestyle that has allowed Thais to be accustomed to living in hot and humid conditions. The traditional Thai lifestyle includes wearing light clothes, use of natural ventilation (i.e., windows), and the use of electric fans.

In Figure 5.18 the master bedroom's psychrometric plot shows data for both conditioned and unconditioned periods. The plot shows that there were more conditions occurring close to ASHRAE's summer comfort zone compared to the plot of bedroom-3, which is an unconditioned space on the second floor. The clustered data along the upper rim of ASHRAE's summer comfort zone were the conditions when the air conditioning system was operated. This shows that even when the room was air-conditioned, according to the standard, the conditions were barely comfortable. However, thermal comfort for Thais is different from ASHRAE's as discussed in the literature review. Specifically, the range of Thai resident's thermal comfort is broader than ASHRAE's and exceeds the ASHRAE's summer comfort zone outward by at least 4 °C (7.2 °F). There is also a consideration that the occupants willingly set the thermostat set-point at 26 °C (78.8 °F), this would be the temperature that they preferred or feel comfortable with during sleeping. Therefore, through interviews it was found that thermal conditions in the master bedroom, when the air conditioning system is operated, are considered as comfortable conditions for the case-study house's occupants.

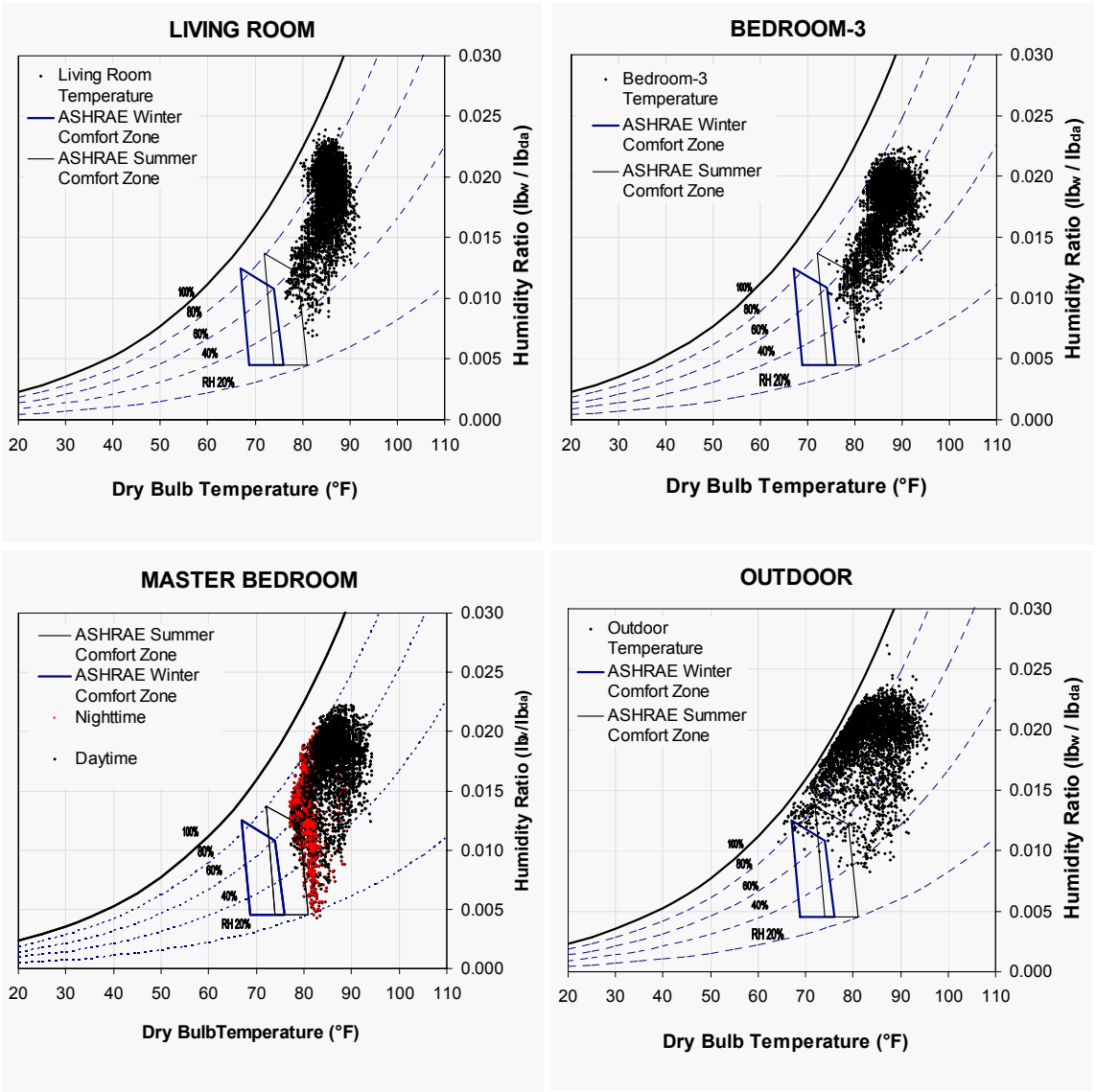


Figure 5.18 *Measured Thermal Conditions at the Case-Study House (June – December 2000).*

5.3 Building Energy Use

This section discusses the case-study house's electricity consumption during seven months of monitoring thermal conditions in the spaces from June to December 2000. This section also discusses electricity consumption of Thai residences by building type in order to compare them to the case-study house's electricity consumption.

5.3.1 Electricity Consumption in the Thai Residential Buildings

In 2000, Thailand's total electricity consumption was 87,597 GWh, which was consumed by four sectors: industrial, commercial, residential, agricultural, and other (EPPO, 2003). Figure 5.19 shows the electricity consumption of these sectors in a pie chart. From the chart, Thai residences consumed about 22 percent of the total electricity consumption of the country. Of this 22 percent, electricity was consumed by three residential building types (see Table 5.1).

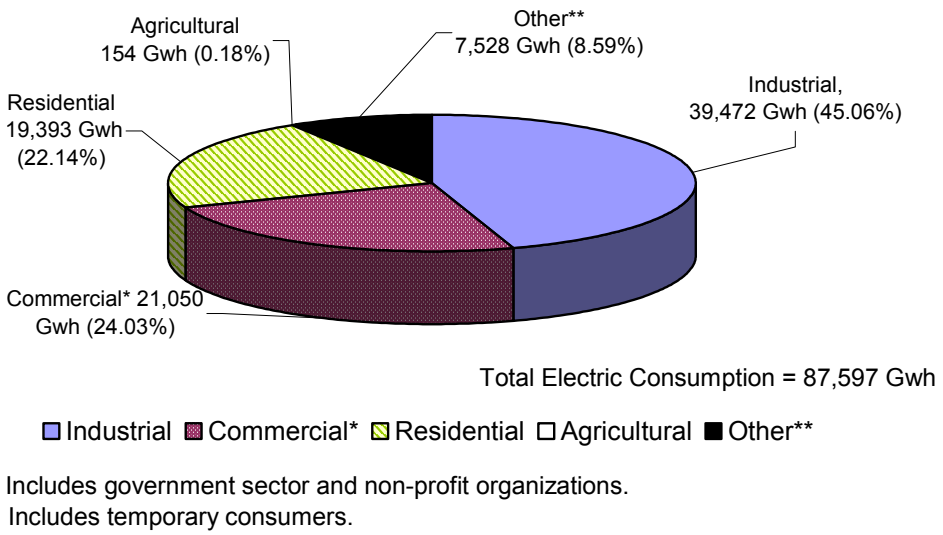


Figure 5.19 *Thailand Electricity Consumption in 2000 by Economic Sectors(EPPO, 2003).*

Table 5.1 presents the residential electricity consumption and percentage of each building type to the total residential electricity use in 2000. The residential electricity was consumed by three housing types: 1) detached houses, 2) rowhouse/town houses, and 3) apartment/condominiums. Table 5.1 shows that about one half (49 percent) of residential energy use was consumed by detached houses, while rowhouse/townhouses and

apartment/condominiums consumed 40 and 11 percent of the total residential energy use, respectively.

TABLE 5.1

2000 Thai Residential Electricity Consumption by Building Type (MEA, 2000; EPPO, 2003)

Housing Type	Electricity Consumption 2000					
	MEA†		PEA††		Total (MEA+PEA)	
	GWh	%	GWh	%	GWh	%
Detached Houseε	2,847	41	6,644	53	9,491	49
Small Detached House*	187	3	2,067	17	2,255	12
Large Detached House**	2,660	39	4,577	37	7,236	37
Rowhouse/Townhouseε	2,071	30	5,625	45	7,695	40
Apartment/Condominiumε	1,964	29	242	2	2,207	11
Total (Actual Data)	6,882	100	12,511	100	19,393	100

† Electricity sales from Metropolitan Electricity Authority of Thailand (MEA, 2000).
†† Electricity sales from Provincial Electricity Authority of Thailand (EPPO, 2003).
* Monthly electricity consumption is less than 150 kWh.
** Monthly electricity consumption is more than 150 kWh.
ε Electricity consumption is estimated from the percentage of residential energy consumption for each housing type in 1998 (EGAT, 1998).

As mentioned earlier in this chapter, the case-study house is located in the vicinity of Bangkok. Therefore, comparing its electricity use with residential buildings that are in the Bangkok Metropolitan area is more appropriate than comparing it to residential buildings in the provincial area. Annual and monthly electricity use per household in the Bangkok Metropolitan area is presented in Table 5.2. Annual energy consumption per household was calculated by dividing the annual energy use of each housing type by the number of houses in each housing

type. The case-study house was considered as a large detached house, since its monthly energy use was more than 150 kWh (MEA, 2000). Comparison of the case-study house's energy use with the energy use of large detached houses was therefore considered the most appropriate. However, there were no statistics about the number of small and large detached houses. Thus, only annual and monthly energy consumption of the detached houses, which combined small and large detached houses, were used to compare with the case-study house's energy use.

TABLE 5.2

Number of Thai Residential by Housing Types and Energy Consumption per Housing Unit in Bangkok Metropolitan Area, 2000

Housing Type	Number of Households*		Energy Consumption		Energy Consump. per Household	
	Household	%	GWh	%	Annually (KWh)	Monthly (KWh)
Detached House	898,055	50.8	2847	41	3170	264
Small Detached House**	N/A		187	3		
Large Detached House***	N/A		2660	39		
Rowhouse/Townhouse	645,256	36.5	2071	30	3209	267
Apartment/Condominium	224,514	12.7	1964	29	8749	729
Total	1,767,825	100	6882	100	3893	324

* NSO 2000
** Electricity consumption less than 150 kWh/month
*** Electricity consumption more than 150 kWh/month

From Table 5.2, the average annual and monthly electricity consumption per household for detached houses and rowhouse/townhouse was about the same. Interestingly, the annual and monthly electricity consumption per household for apartment/ condominium category was about 2.7 times higher than that of the detached house and rowhouse/townhouse category. The reason for this is unknown since there no reports or studies of Thai residential building's energy use per household by building type could be located. Regardless, since only the energy use per household for detached houses is needed to compare with the case-study house's energy use, no

further review was performed. The next section presents the case-study house's electricity consumption compared to the average electricity use per household in the Bangkok Metropolitan area.

5.3.2 Monthly Energy Use of the Case-Study House

Utility bills for the case-study house were obtained from the residents. Seven months of electricity use, from June to December 2000, are presented in Table 5.3. In the table, the monthly average daily electricity use was calculated by dividing each month's electricity use by the actual number of days in the billing cycle. The resultant monthly average daily electricity use was then used to calibrate the case-study house base-case simulation model, which is presented in Chapter VII.

TABLE 5.3

Actual Electricity Consumption of the Case-Study House from June to December 2000

Billing Period			Electricity Bills		
Month	From	To	Number of Days	Electricity Use (kWh)	Avg Elec. Use (kWh/day)
June	29-May-00	28-Jun-00	30	450	15.00
July	28-Jun-00	28-Jul-00	30	414	13.80
August	28-Jul-00	29-Aug-00	32	454	14.19
September	29-Aug-00	28-Sep-00	30	334	11.13
October	28-Sep-00	28-Oct-00	30	451	15.03
November	28-Oct-00	28-Nov-00	31	382	12.32
December	28-Nov-00	28-Dec-00	30	405	13.50
June to Dec.	29-May-00	28-Dec-00	213	2890	13.57

For the period from June to December 2000, the average electricity use was 413 kWh per month, which is approximately 56 percent more than the average electricity use per month of a detached house (264 kWh per month). Thus, this research does not assume that the case-study represents all detached houses, in regards to the electricity use, in the Bangkok

Metropolitan area.

One of the reasons for the above average electricity use in the case-study house is that the number of appliances in the case-study house were more than an average household contained. For example, the case-study house had two refrigerators, while there were only 0.85 refrigerators per household in the municipal area (NSO, 2000). In addition, the case-study house had two air conditioning systems, while there were 0.25 air conditioning units per household in the municipal area (NSO, 2000). Energy use by the water heater is also significant. Table 5.4 presents the estimation of electricity use by the water heater of the case-study house. The residents used the hot water only for showering.

TABLE 5.4

Estimated Electricity Consumption by a Water Heater of the Case-Study House

Month	Water Temp.* (◦F)	Water Temp. for Showering** (°F)	Temp. Difference (◦F)	Hot Water Use*** (lbs / day)	Energy Use for DHW Use per Day (Btus)	Energy Use for DHW Use per Day (kWh)	Days in the billing cycle (days)	Vacation (days)	Actual Living Days (days)	Estimated Energy Use for DHW Use per Month (kWh)
June	82.4	110	27.6	625.5	17263.8	5.06	30	0	30	152
July	82.8	110	27.2	625.5	17038.6	4.99	30	0	30	150
August	82.8	110	27.2	625.5	17038.6	4.99	32	0	32	160
September	81.5	110	28.5	625.5	17826.8	5.22	30	4	26	136
October	81.7	110	28.3	625.5	17714.2	5.19	30	0	30	156
November	79.7	110	30.3	625.5	18952.7	5.55	31	0	31	172
December	81.0	110	29.0	625.5	18164.5	5.32	30	0	30	160

* Estimated monthly water temperature by using monthly average ambient temperatures from weather data (Kusuda, 1965)

** Water Temperature for showering assumed from Stein and Reynolds (1992)

***Calculated from the case-study house's owner information: 40 mins of DHW per day (estimated flow rate of 2 GPM)

According to the calculated hot water electricity use in Table 5.4, during the seven-month period, the energy used by water heater was accounted for 37.6 percent of the total energy consumption per month. The estimated monthly energy use by the water heater was used to calibrate the hot water energy use of the base-case model in the building simulation in Chapter VII.

The refrigerators monthly energy use was calculated from the rated annual electricity energy use (MOST, 1998). Table 5.5 presents rated annual electricity energy use and average hourly and daily energy use of the refrigerators. The estimated monthly refrigerator energy use is presented in Table 5.6. From Table 5.6, the average seven-month energy use for the refrigerators was calculated to be 22 percent of the whole-house energy use.

The energy consumption of the case-study house's air conditioning systems was calculated using the DOE-2 building simulation program. Chapter VII presents results of the simulated energy analysis using a calibrated model, which includes energy use by the air conditioning systems, the water heater, lighting, and equipment.

From the results of the estimated energy use by the water heater and the refrigerators in the case-study house, the monthly electricity energy use of both the water heater and the refrigerators as well as the total monthly electricity use were plotted in Figure 5.20. In the figure, it can be seen that energy use by the water heater and the refrigerators was approximately 60 percent of the total monthly energy use. Thus, reducing the energy use of the water heating and refrigerators offers a significant opportunity for the case-study residence.

TABLE 5.5

Estimated Electricity Consumption by Refrigerators of the Case-Study House (MOST, 1998)

Refrigerator	Size (ft^3)	Rated Annual Energy Use (kWh)	Avg. Hourly Energy Use (kWh)	Avg. Daily Energy Use (kWh)
1 *	14	657	0.075	1.80
2**	6.5	427	0.049	1.17
Total	20.5	1084	0.124	2.97

* Refrigerator in the kitchen, 5 year-old with high standard rating
** Refrigerator on the second floor, 14 year-old with low standard rating

TABLE 5.6

Estimated Monthly Electricity Consumption by Refrigerators in the Case-Study House

Month	Days in the Billing Cycle	Whole-house Monthly Electricity Use (kWh)	Energy Use for Refrigerators per Month	
			(kWh)	(%)
June	30	450	89.1	19.8
July	30	414	89.1	21.5
August	32	454	95.0	20.9
September	30	334	89.1	26.7
October	30	451	89.1	19.8
November	31	382	92.1	24.1
December	30	405	89.1	22.0
Average	-	413	90.4	22.1

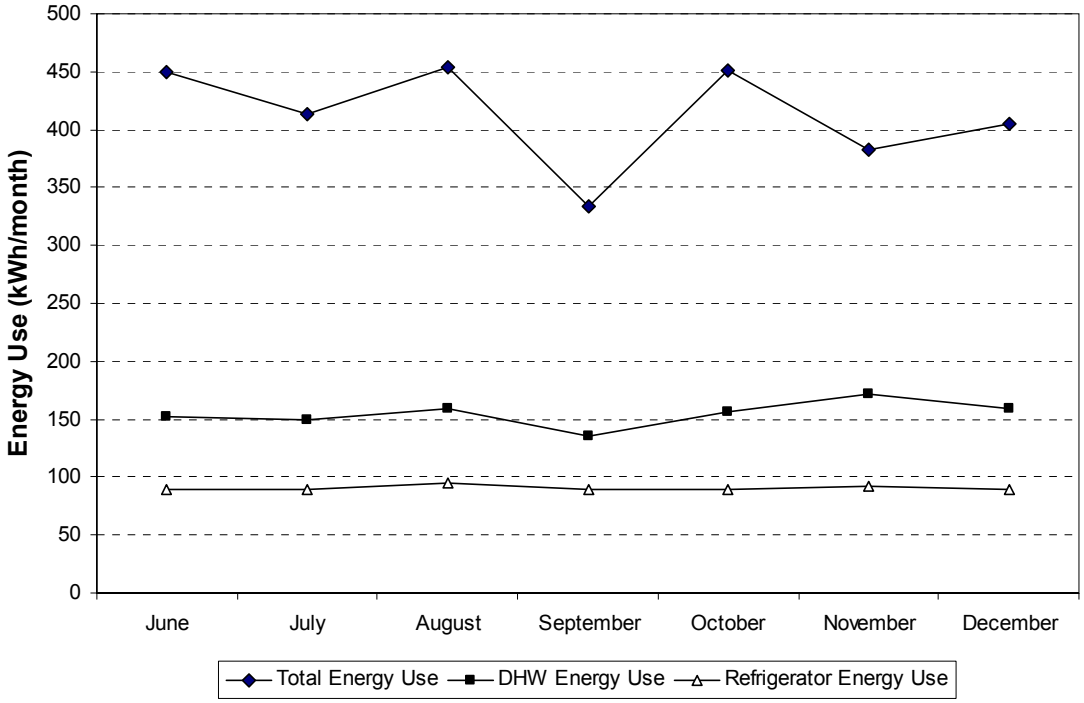


Figure 5.20 *The Case-Study House Monthly Energy Use. The total monthly electricity use is shown plotted with the estimated energy uses of the water heater and the refrigerators.*

5.5 Summary

This chapter has discussed the case-study house, including the measured thermal conditions of the spaces in the house, and the building's energy consumption compared to other similar Thai residences units. The thermal conditions in the house were found to be outside the ASHRAE comfort zone. Energy consumption of the case-study house was found to be above the average energy consumption of detached Thai houses. The averaged DHW and refrigerator energy use were accounted for 37.6 and 22.1 percent of the total energy consumption per month, respectively. Thus, both DHW and refrigerator energy use were account for approximately 60 percent of the total energy consumption per month. Therefore, this is a good opportunity to reduce energy use of the DHW and refrigerator.

CHAPTER VI

DATA ANALYSIS AND RESULTS OF EXPERIMENTS WITH THE HYBRID PHOTOVOLTAIC-THERMAL COLLECTOR AND THE NIGHT SKY COOLING SYSTEM

This chapter presents the measured data, data analyses and the results of experiments with the triple effect photovoltaic-thermal collector/rejecter experiments. This chapter is divided into three sections: 1) thermal performance, 2) electrical performance, and 3) night sky cooling performance.

6.1 Experimental Case 1: Thermal Performance of the PV-T^2 System

The experiments with the thermal performance of the PV-T^2 system utilized the day mode experiment, which included experiments with the electricity production of the system. The day mode experiments were performed over a number of days, with eight clear days of day mode experiments selected for inclusion in the analysis of the thermal performance of the system. A single day of measured data and the results of the thermal collection analysis are presented in Figure 6.1, in Section 6.1.1. The remainder of the measured data and the results of all the experiments are presented in Appendix B. Selected data points, which were used to characterize the thermal performance of the PV-T^2 system, are presented in Table 6.1.

6.1.1 Results from the Thermal Solar Collector System

Figure 6.1 presents the measured data and the results of the analysis of the experiments with the thermal performance of the hybrid PV-T^2 system conducted on December 20, 2002. In Figure 6.1, graphs (a), (b), and (c) show the measured data from the experimental box. Graphs (d) shows the measurements of weather data which was collected from a nearby building with a weather station (i.e., the Zachary building). Graphs (e) and (f) show the gross collected thermal energy and the collected solar thermal energy by using two different calculation methods. Each graph is discussed in the following Section.

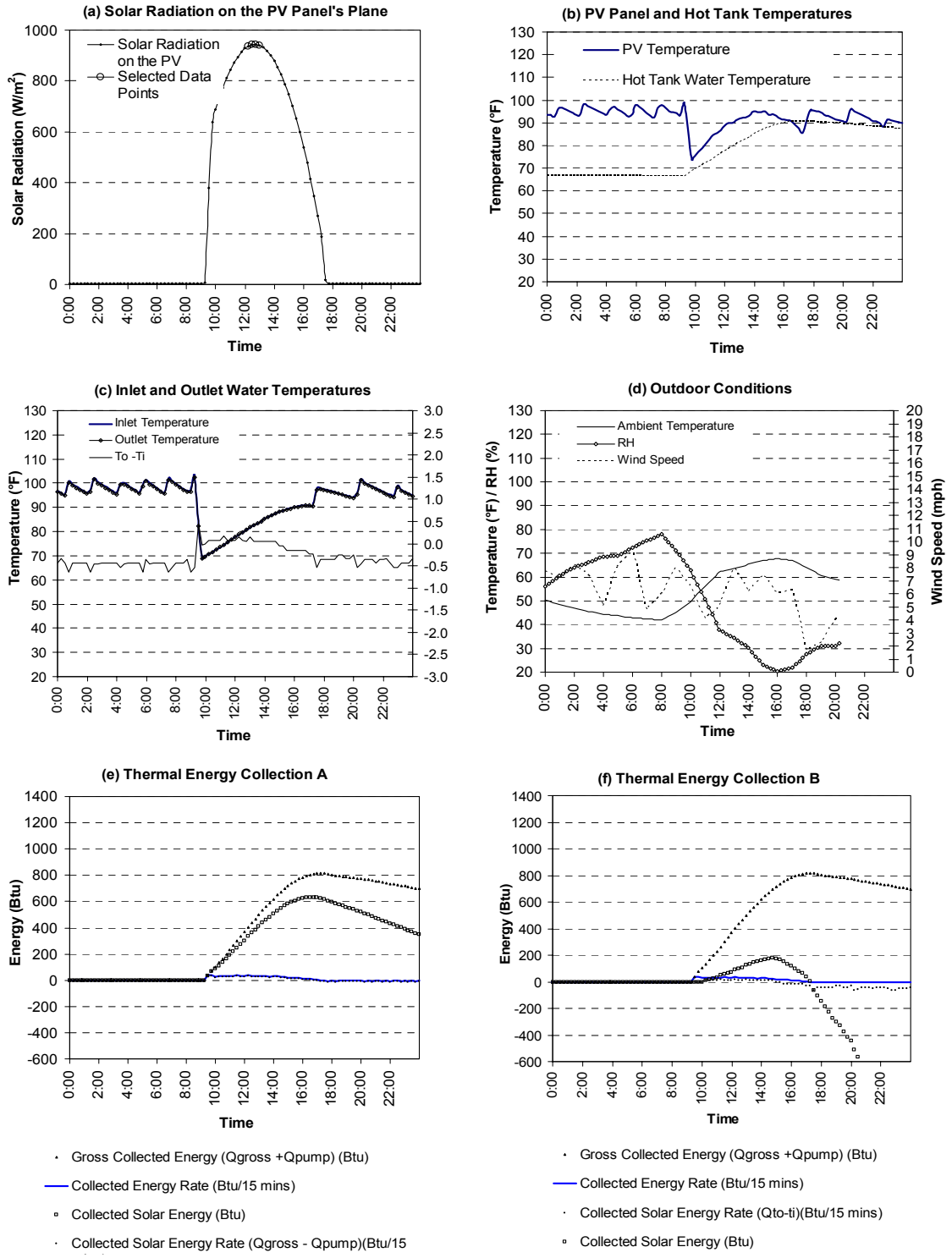


Figure 6.1 *Thermal Energy Collection of the Hybrid PV-T² System: Measured Data and Results of the Experiment Conducted on December 20, 2002.*

Graph (a) shows the total solar radiation measured in the collector plane, which was tilted at a 30 degree angle toward to south. On December 20, 2002, the sun rose at approximately 7:30 a.m. However, the collector was blocked from direct solar radiation by the penthouse walls on the roof of the Architecture Building A, where the experimental box was located. The collector was shaded from the sun's rays until approximately 8 a.m. However, the system was switched to the anti-freezing mode the night before the experiment due to the cold weather, so the collector and the radiation sensor were both covered (see Appendix B.5 for the details of the anti-freezing mode). This can be seen by the straight line on the plotted data in graph (a); solar radiation fell onto the collector when it was uncovered at 9:30 a.m. Since only a few points near to the solar noon hour were used for the analysis the missing data in the morning hours did not affect the collector's performance parameters.

As mentioned above, the system was operated in the anti-freezing mode the night before the experiment, although the ambient temperatures did not reach the freezing point, as seen in graph (d). This system switch was a necessary precaution to prevent the possible freezing of water in the collector and the pipes, especially the exterior ones. Placing the system in the anti-freezing mode caused the PV's temperatures to move up and down as shown in graphs (b) and (c). This was due to the operation of the water heater, which was turned on and off by its thermostat. The thermostat was set at a medium set-point temperature (i.e., warm water: 100 °F). This temperature was sufficient to prevent freezing. The system was switched from the anti-freezing mode to the day mode experiment at 9:30 a.m., as seen by the drop in the PV temperature and inlet and outlet temperatures shown in graphs (b) and (c). Graph (b) also shows the hot tank temperature, which remained constant at approximately 67 °F, prior to the previous day mode experiment. This was due to the cold weather. Thus, the radiator was not used to cool the hot tank water since the water temperature was already low, which was appropriate for the day mode experiment.

The temperature of the PV increased from 74 °F in the morning to a peak of approximately 95 °F in the afternoon (from 2:00 p.m. to 3:00 p.m.), while the peak solar radiation (about 950 W/m^2 in the collector plane) occurred from noon to 1:00 p.m. The highest ambient temperature (68 °F) of the day occurred at 4:00 pm. The ambient temperature reached its lowest point (42 °F) at approximately 8:00 a.m. The PV panel temperature decreased after 3:00 p.m. and reached the lowest point (85 °F) at 5:00 p.m. when the experiment was concluded. Hot tank water temperatures increased from the constant temperature (67 °F) at the beginning of the experiment to the highest temperature (91 °F) at the end of the experiment

(5:00 p.m.), then slowly declined when the sun had set. This yielded a temperature difference of 24 °F.

Graphs (e) and (f) in Figure 6.1 show the results of the analysis of the thermal energy collection of the PV-T^2 system. The gross thermal energy collection was determined by calculating the heat gain rate (in 15 minute increments) of the water in the hot tank. These calculated 15 minute heat gains represent the cumulative gross thermal energy gain. The cumulative gross thermal energy collection is calculated by Equation 6.1.

$$Q_{th,g} = \sum_{j=1}^{n} m \cdot c_p \cdot (t_{h,j+15} - t_{h,j}) \tag{6.1}$$

where

$Q_{th,g}$ = Gross cumulative thermal energy output from the hybrid PV-T^2 collector system and the water circulating pump, Btu

m = Mass flow rate of the transfer fluid (water), lb/15-min

c_p = Specific heat of the transfer fluid (water), Btu/(lb · °F)

$t_{h,j}$ = Temperature of water in the hot tank at the jth time interval, °F

$t_{h,j+15}$ = Temperature of water in the hot tank at the jth + 15 mins time interval, °F

The results of the heat gain rate and gross thermal energy collections are shown in graphs (e) and (f). Both graphs show the same results of the thermal energy collection for the same period, which allows for a comparison by two different methods: 1) the calculation of water temperature gain in the hot tank, and 2) the integration of water temperature differences in inlet and outlet temperatures. The first method involves heat gain from the pump, while the second method does not.

The cumulative collected solar heat gain rate (method 1), was calculated from the water temperature changes in the hot tank (Equation 6.2), and excludes the heat of the pump.

$$\dot{Q}_{th,sol-Tank} = \dot{m} \cdot c_p \cdot (t_{h,j+15} - t_{h,j}) - \dot{Q}_p \tag{6.2}$$

Where

$\dot{Q}_{th,sol-Tank}$ = Cumulative collected solar energy rate that is calculated by the change of hot tank water temperature and energy gain from the pump, Btu

$\dot{m}$ = Mass flow rate of the transfer fluid, lb/15 min

c_p = Specific heat of the transfer fluid (water), Btu/(lb · °F)

$t_{h,j+15}$ = Temperature of water in the hot tank at the jth + 15 mins time interval, °F

$t_{h,j}$ = Temperature of water in the hot tank at the jth min time interval, °F

$\dot{Q}_p$ = Heat gain rate from the pump (see Appendix B.7)

Graph (e) shows the results of the collected solar energy calculation using method 1 and compares it to the total heat gain (gross collected energy). The results show that the daily collected solar energy (the maximum collected solar energy before the system began losing heat) was approximately 75 percent of the gross collected energy. The peak of the collected solar energy and gross collected energy occurred at approximately 5:00 p.m. After 5:00 p.m. the system began losing heat as the sun was setting. At this time the gross collected energy and the collected solar energy decreased, as seen in graph (e).

The collected solar heat gain rate (method 2), which is calculated from the inlet and outlet water temperatures, is calculated by Equation 6.3.

$$\dot{Q}_{th,sol-ie} = \dot{m} \cdot c_p \cdot (t_{f,e} - t_{f,i}) \tag{6.3}$$

where

$\dot{Q}_{th,sol-ie}$ = Collected solar energy rate that is calculated by inlet and outlet temperatures, Btu/15-min

$\dot{m}$ = Mass flow rate, lb/15-min

c_p = Specific heat of the transfer fluid (water), J/(kg · °C) [Btu/(lb · °F)]

$t_{f,e}$ = Temperature of outlet water, °C (°F)

$t_{f,i}$ = Temperature of inlet water, °C (°F)

Graph (f) shows the results of the collected solar energy calculation using method 2 and compares it to the total heat gain (gross collected energy). The results show that the daily collected solar energy (i.e., the maximum collected solar energy before the system began losing heat) was approximately 25 percent of the gross collected energy. The peak solar energy collection rate occurred at approximately 3:00 p.m., while the total gross collected energy occurred when the system was shut off at 5:00 p.m.

The comparison of the two calculation methods shows a difference between the heat gain rates which is caused from the heat gain rate from the pump. From the null test of the pump's heat gain rate, it was found that the pump contributed heat to the system in the range of 3 to 24 Btu/15 min (see Appendix B). The high rates occurred when the water temperature in the system was relatively cool (when the experiment had just begun), while the low rates occurred when the water temperature in the system was relatively hot. In the analysis, the averaged pump heat gain (6 Btu/15-min) of the system was used in the solar heat gain rate calculation (method 1).

Measured data from the eight day mode experiment days were selected to be analyzed for the thermal performance of the hybrid PV-T^2 collector. The measured data and the results of all the experiment days are presented in Appendix B. Table 6.1 shows the measured data and the results of the four data points of the eight experiment days that were used to analyze the thermal performance of the hybrid PV-T^2 collector in the next section.

TABLE 6.1

Measured Data and Results of Thermal Solar Experiments

DATE TIME	t_p (°F)	$t_{f,i}$ (°F)	$t_{f,e}$ (°F)	t_h (°F)	t_a (°F)	$t_{f,e}$ -$t_{f,i}$ (°F)	I_t (W/sq.m)	I_t (Btu/sq.ft)	Q_{ther} (Btu/h)	I_t*A_g (Btu)	η (fraction: 0 to 1)	$t_{f,i}$ - t_a (°F)	$(t_{f,i}-t_a)/I_t$ °F.Hr.sq.ft/Btu
11/6/02 12:00 PM	98.33	86.08	86.14	85.84	67.29	0.06	971.63	308.01	28.52	328.03	**0.087**	18.79	**0.061**
11/6/02 12:15 PM	99.73	87.58	87.64	87.34	67.90	0.06	974.57	308.94	28.22	329.02	**0.086**	19.68	**0.064**
11/6/02 12:30 PM	100.83	88.98	89.04	88.74	68.47	0.06	976.05	309.41	27.95	329.52	**0.085**	20.52	**0.066**
11/6/02 12:45 PM	101.03	90.28	90.34	90.04	68.86	0.06	972.36	308.24	27.70	328.28	**0.084**	21.42	**0.070**
11/7/02 12:00 PM	95.22	78.56	78.73	78.33	67.01	0.16	961.32	304.74	78.58	324.54	**0.242**	11.56	**0.038**
11/7/02 12:15 PM	95.72	79.97	80.13	79.83	67.79	0.16	965.00	305.90	78.31	325.79	**0.240**	12.17	**0.040**
11/7/02 12:30 PM	98.03	81.37	81.53	81.23	68.58	0.16	967.94	306.84	78.03	326.78	**0.239**	12.79	**0.042**
11/7/02 12:45 PM	98.33	82.77	82.93	82.64	69.25	0.16	962.05	304.97	77.76	324.79	**0.239**	13.52	**0.044**
12/20/02 12:15 PM	89.71	78.66	78.83	78.53	66.02	0.16	937.01	297.03	78.56	316.34	**0.248**	12.64	**0.043**
12/20/02 12:30 PM	89.91	79.67	79.73	79.53	66.02	0.06	942.16	298.67	29.76	318.08	**0.094**	13.65	**0.046**
12/20/02 12:45 PM	91.21	80.67	80.73	80.43	66.72	0.06	942.90	298.90	29.57	318.33	**0.093**	13.95	**0.047**
12/20/02 1:00 PM	91.82	81.57	81.73	81.43	67.41	0.16	939.22	297.73	77.99	317.08	**0.246**	14.16	**0.048**
1/6/02 12:15 PM	97.63	87.48	87.54	91.25	68.11	0.06	894.28	283.49	28.24	301.92	**0.094**	19.37	**0.068**
1/6/02 12:30 PM	98.83	88.38	88.44	91.05	68.80	0.06	904.60	286.76	28.07	305.40	**0.092**	19.58	**0.068**
1/6/02 12:45 PM	99.83	89.38	89.44	90.85	69.51	0.06	904.60	286.76	27.87	305.40	**0.091**	19.88	**0.069**
1/6/02 1:00 PM	100.33	90.18	90.24	90.75	69.51	0.06	902.39	286.06	27.72	304.65	**0.091**	20.68	**0.072**
1/16/03 12:30 PM	54.47	36.17	36.66	35.71	50.56	0.49	956.16	303.10	237.49	322.80	**0.736**	-14.38	**-0.047**
1/16/03 12:45 PM	56.55	39.29	39.70	38.85	51.27	0.41	959.84	304.27	198.00	324.05	**0.611**	-11.98	**-0.039**
1/16/03 1:15 PM	52.58	33.19	33.74	32.68	51.27	0.55	945.85	299.83	267.23	319.32	**0.837**	-18.08	**-0.060**
1/16/03 1:30 PM	52.20	33.09	33.64	32.57	51.27	0.55	932.59	295.63	267.25	314.85	**0.849**	-18.18	**-0.062**
5/31/03 1:30 PM	121.60	112.80	112.90	112.60	101.66	0.10	892.08	282.79	48.54	301.17	**0.161**	11.14	**0.039**
5/31/03 1:45 PM	122.10	113.80	113.90	113.60	102.32	0.10	896.49	284.19	48.54	302.66	**0.160**	11.48	**0.040**
5/31/03 2:00 PM	123.90	114.80	115.00	114.60	102.97	0.20	896.49	284.19	97.08	302.66	**0.321**	11.83	**0.042**
5/31/03 2:15 PM	124.00	115.80	115.90	115.60	103.06	0.10	889.87	282.09	48.54	300.42	**0.162**	12.74	**0.045**
6/7/03 1:30 PM	121.20	111.30	111.40	111.10	96.46	0.10	906.81	287.46	48.54	306.14	**0.159**	14.85	**0.052**
6/7/03 1:45 PM	121.80	112.30	112.40	112.10	97.24	0.10	907.54	287.69	48.54	306.39	**0.158**	15.06	**0.052**
6/7/03 2:00 PM	122.30	113.30	113.40	113.10	98.03	0.10	907.54	287.69	48.54	306.39	**0.158**	15.27	**0.053**
6/7/03 2:30 PM	123.00	115.00	115.10	114.00	99.42	0.10	889.87	282.09	48.54	300.42	**0.162**	15.58	**0.055**
7/3/03 12:45 PM	116.00	104.90	105.10	104.60	103.98	0.20	705.72	223.71	97.08	238.25	**0.407**	0.92	**0.004**
7/3/03 1:00 PM	113.00	106.00	106.10	105.70	103.60	0.10	637.95	202.23	48.54	215.37	**0.225**	2.41	**0.012**
7/3/03 1:15 PM	119.30	107.20	107.50	106.90	103.21	0.30	905.33	286.99	145.62	305.65	**0.476**	3.99	**0.014**

Note: There are three data values on July 3,2003, since there was an error of the measured data at 1:30 p.m. That error was omitted.

6.1.2 Thermal Performance of the Hybrid PV-T^2 System

This section presents the experimental results of the thermal performance of the PV-T^2 collector. The thermal efficiency of the PV-T^2 collector was determined using a Hottel-Whiller-Newton Plot, displayed in Figure 6.2.

The measured data and results from the eight experimental days are shown in Figure 6.2. The measured data ($(t_{f,i}-t_a)/I_t$) is plotted on the X-axis, and the experimental results of the thermal efficiency of the collector are plotted on the Y-axis. Most of the plotted data ($(t_{f,i}-t_a)/I_t$) are positive except for the results of the experiment conducted on January 16, 2003, which were specifically designed to result in negative results of $(t_{f,i}-t_a)/I_t$. ASHRAE Standard 96-1980

(ASHARE, 1989) recommends that at least one value of $(t_{f,i}-t_a)/I_t$ should be of a negative value. Negative values of $(t_{f,i}-t_a)/I_t$ were accomplished by setting inlet water temperatures much lower than the ambient air temperatures at solar noon. As shown in Table 6.1, all inlet water temperatures except those on January 16, 2003, were higher than the ambient temperatures. To accomplish this ice water was used for the day mode experiment on January 16, 2003, in order to make the inlet water temperature much lower than the ambient temperature. A significant amount of ice was put into the hot tank, causing the hot tank water to reach near-ice temperatures (32.6 °F to 38.9 °F) during the experiment.

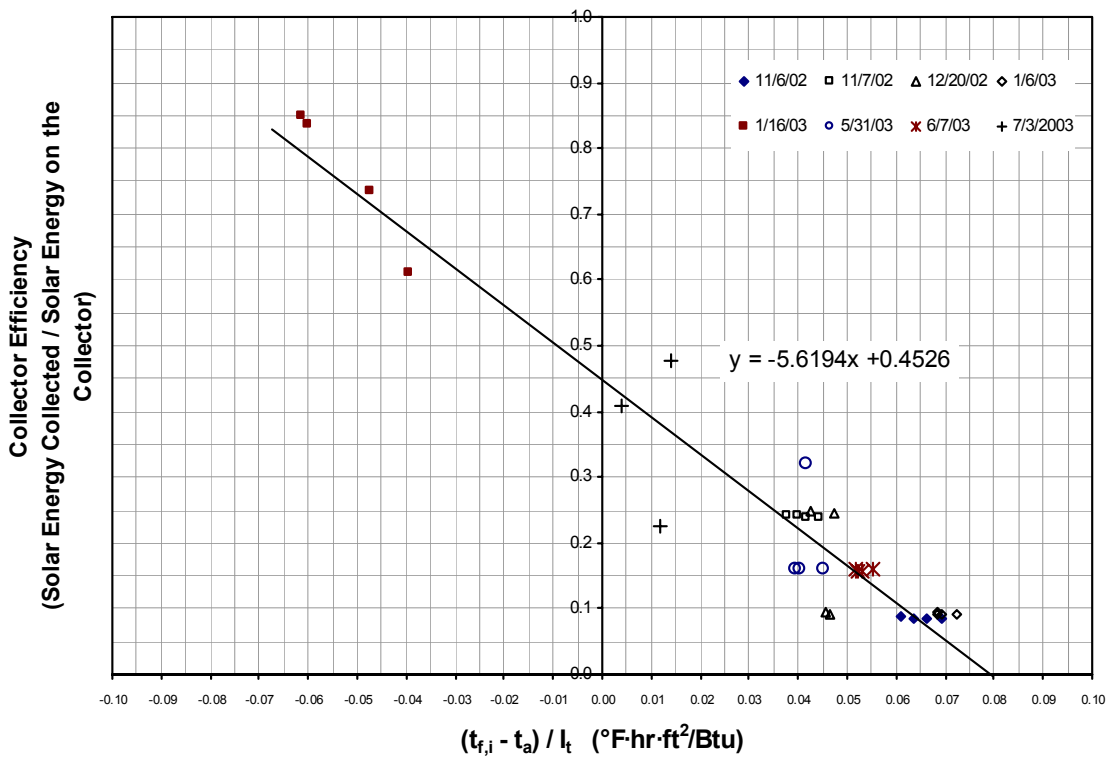


Figure 6.2 *Thermal Performance of the Hybrid PV-T² System.*

A regression line and a mathematical expression of that regression line, which represents the thermal performance of the hybrid PV-T^2 collector, were generated from the experimental data. The linear regression shows a maximum efficiency of 45 percent when the parameter $(t_i-t_a)/I_t$ is zero, and has zero efficiency when the parameter $(t_i-t_a)/I_t$ is approximately 0.08 °F ·hr ·ft^2/Btu.

The next section compares of the thermal performance of the hybrid PV-T^2 collector with other solar collectors. A linear equation was used to calculate two thermal performance parameters: the Test Slope (FrUL) and the Test Intercept ($Fr\tau\alpha$). These two parameters were required for an analysis of the hybrid PV-T^2 system with the F-Chart program. Section 6.1.4 presents a calculation of these two parameters.

6.1.3 A Comparison of the Performance of the Hybrid-PV-T^2 System and a Selection of Solar Thermal Collectors

The thermal performance of the hybrid PV-T^2 collector was compared to published data for ten solar collectors. In Figure 6.3, the measured data and the linear regression line from Figure 6.2 were superimposed on a published graph of the performance of a variety of solar collectors presented by Newton and Gilman (1981).

From those comparisons of solar collectors displayed in Figure 6.3, it can be concluded that the performance of the hybrid PV-T^2 is in the range of $(t_i-t_a)/I_t$, from 0 to 0.08 °F ·hr ·ft^2/Btu , which is less efficient than the performance of an unglazed collector. The maximum efficiency (i.e., when the parameter $(t_i-t_a)/I_t$ is zero), of the hybrid PV-T^2 collector is 45 percent, which is very close to that of two liquid types: a plastic lense cover with tracking concentration (45 percent), and an evacuated tube (42 percent). In summary, the thermal efficiency of the hybrid PV-T collector is relatively low as compared to those solar collectors presented in Figure 6.3.

There are several factors contributed to the low efficiency. First, although there were attempts to attach the copper plates to the back surface of the PV panel using the conductive paste, there could be air gaps between the copper plates and the back surface of the PV panel. These air gaps would resist the heat conduction from the PV panel to the copper plates. Second, there were two copper pipes that carry heat from the copper plates spaced at 6”. The spacing of the pipes could also be a factor that reduced thermal efficiency of the PV panel. These factors reduced the thermal efficiency of the hybrid PV-T collector and therefore need to be study in

the future.

There are ways to improve the thermal efficiency of the hybrid PV-T collector. The thermal performance of the hybrid PV-T collector, which is relatively low, could be improved by adding a sheet of glass in front of the collector (Tripanagnostopoulos et al., 1996). The glazing would help prevent the collected heat from escaping the PV panel's surface. A reflector (such as a flat aluminum sheet) would also help to increase solar energy on the PV panel's surface, thus increase the efficiency of the system.

6.1.4 Generating of Solar Collector Parameters for Analysis of the Solar Collector System in the F-Chart Program

The Test Slope (FrUL) and the Test Intercept ($Fr\tau\alpha$) are the two experimental parameters required for on analysis of the hybrid PV-T system in the F-Chart program. Figure 6.4 shows the two parameters that were calculated from a linear regression of the data points.

The calculation of the test slope (FrUL) and the test intercept ($Fr\tau\alpha$) are described in the following steps.

1) From the regression equation: $y = -5.6194x + 0.4526$ (6.1)

The Test Intercept is the value of y when x is zero:

$$y \text{ intercept} = Fr\tau\alpha = 0.4526$$

2) The Test Slope of the test data is $|-5.6194|$, which represents FrUL.

From these calculations, the test slope (FrUL) is 5.6194 Btu/hr $\cdot ft^2 \cdot {}^{o}F$, and the test intercept ($Fr\tau\alpha$) is 0.45 %.

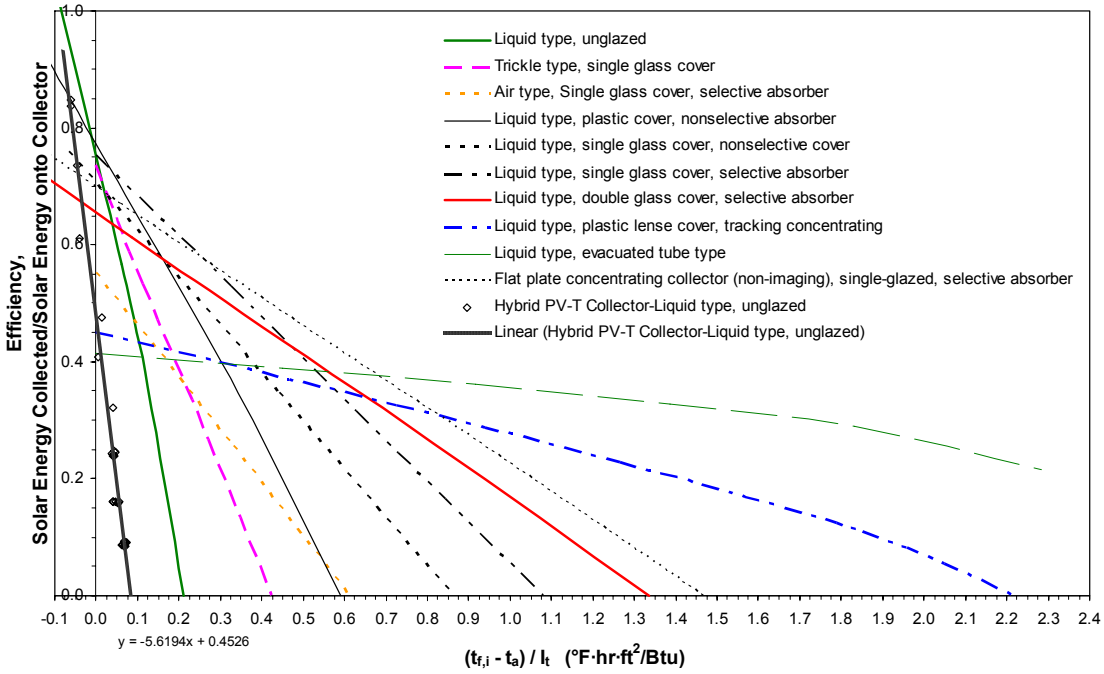


Figure 6.3 *Thermal Performance of the Hybrid PV-T^2 System as Compared to the Performance of a Variety of Solar Collectors. The measured data were superimposed on the published performance of the solar collectors by A.B. Newton and S.F.Gilman (1981). (Reprinted with permission. 1981 Solar Collector Performance Manual © American Society of Heating, Refrigerating and Air Conditioning Engineers, Inc.,* www.ashrae.org*).*

6.2 Experimental Case 2: Electrical Performance of the PV-T^2 System

The experiment concerning the electrical performance of the PV-T^2 system was part of the day mode experiment, which included the experiment with the thermal performance of the system that was described in Section 6.1. Eight days of day mode experiments were selected for inclusion in this analysis of the thermal performance of the system. Of those eight experimental days, five were included in experiments with the electrical performance. In the early experimental days, there was a problem with the resistor circuit board that served as the load on the PV system. During this period, the resistors were overloaded by the electricity produced by the PV, and were destroyed. Therefore, there was no measured electrical output from the PV system during the earlier day mode experiments. The broken resistor circuit board was later replaced with a new resistor circuit board with a higher electrical resistance so it could

handle the electrical load from the PV. One day of measured data and the results of electrical output analysis are presented in Figure 6.5 in Section 6.2.1. The measured data and the results of all the experiment days are presented in Appendix B. Selected data points that were used to analyze the electrical performance of the system are presents in Table 6.2.

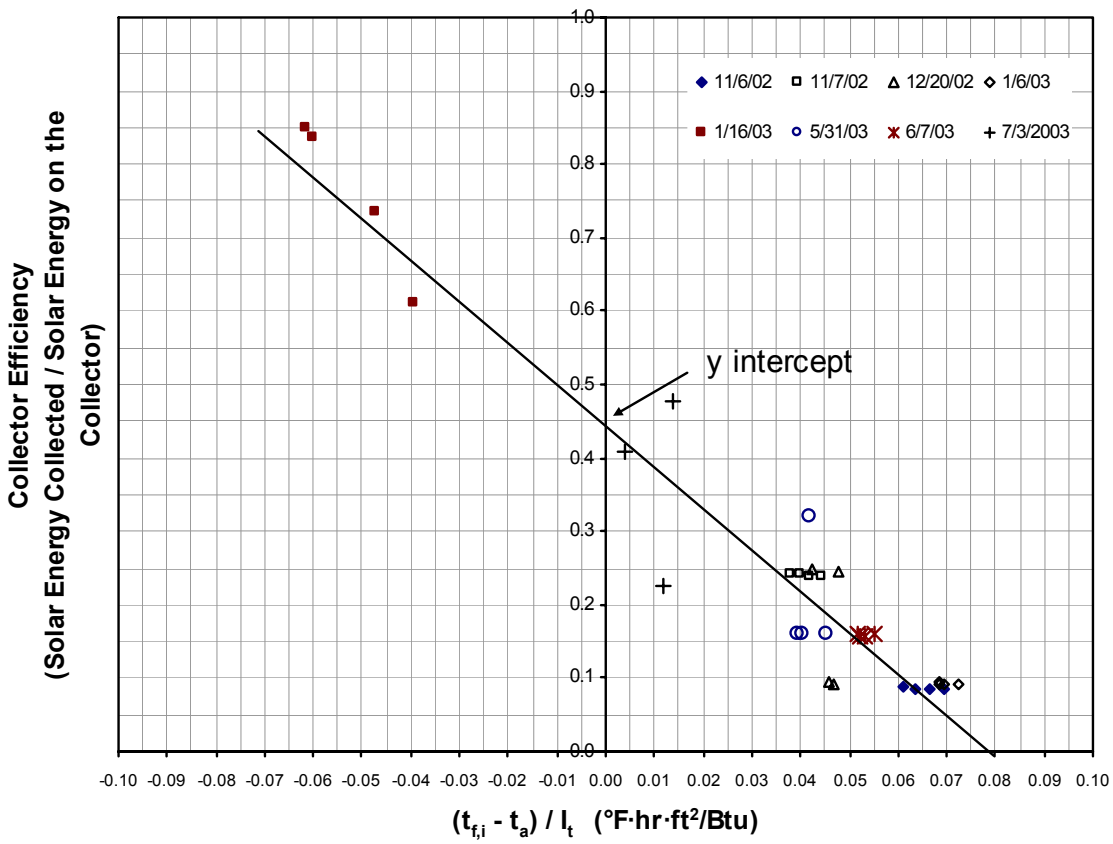


Figure 6.4 *Calculation of Thermal Performance Parameters of the Hybrid PV-T^{2}System.*

6.2.1 Results from the Photovoltaic System

Figure 6.5 presents the measured data and the results of the electrical performance analysis of the hybrid PV-T^2 system conducted on December 20, 2002. In Figure 6.4, Graph (e) shows the measured voltage and amperage (current) outputs from the PV panel. Graph (f) shows the electrical power output from the PV panel. The measured data from the experimental box and the corresponding weather data [Graph (a), (b), (c) and (d)] collected on December 20,

2002, shown in Figure 6.1, are also shown in Figure 6.5.

From Figure 6.5, it can be seen that as the PV-T^2 unit was uncovered at approximately 9:30 a.m., the PV began to immediately produce electricity as shown in graphs (a) and (f). As the solar radiation increased during the morning (i.e., prior to the local solar noon), the PV panel's power output also increased. The measured output power reached its maximum at 7.86 Watts at the solar noon, while the temperature of the PV panel increased to 90 °F from, approximately 74 °F when the experiment began. The measured solar radiation on the PV panel's plane was 942 Watts/m^2; the solar energy that fell on the PV surface was 93.35 Watts (the PV's surface area is 0.01 m^2) (see Table 6.2). This yielded on the efficiency of the PV array of 8.4 percent. After the PV's output power reached its peak at the solar noon, it stayed above 7 watts until approximately 3:00 p.m. when it rapidly decreased as the sun's intensity decreased.

Table 6.2 presents the measured data, weather data and the results of the PV panel efficiencies of the five experimental days. Only the four data points near solar noon on each experimental day that were used to calculate the PV panel's efficiency are shown in Table 6.2. All data for all days are presented in Appendix B.

The experiment with the electrical performance of the hybrid PV-T^2 system was conducted over a wide range of weather conditions and PV panel temperatures. The experiments conducted on May 31, 2003 and June 7, 2003, were performed in hot weather conditions; the temperatures on both these days at solar noon was approximately 100 °F. On both days the skies were clear with low wind speeds (see Table 6.2). These conditions caused the PV panel's temperatures to be very high (around 120 °F) resulting in relatively low power outputs for the PV panel, which were about 6.6 Watts.

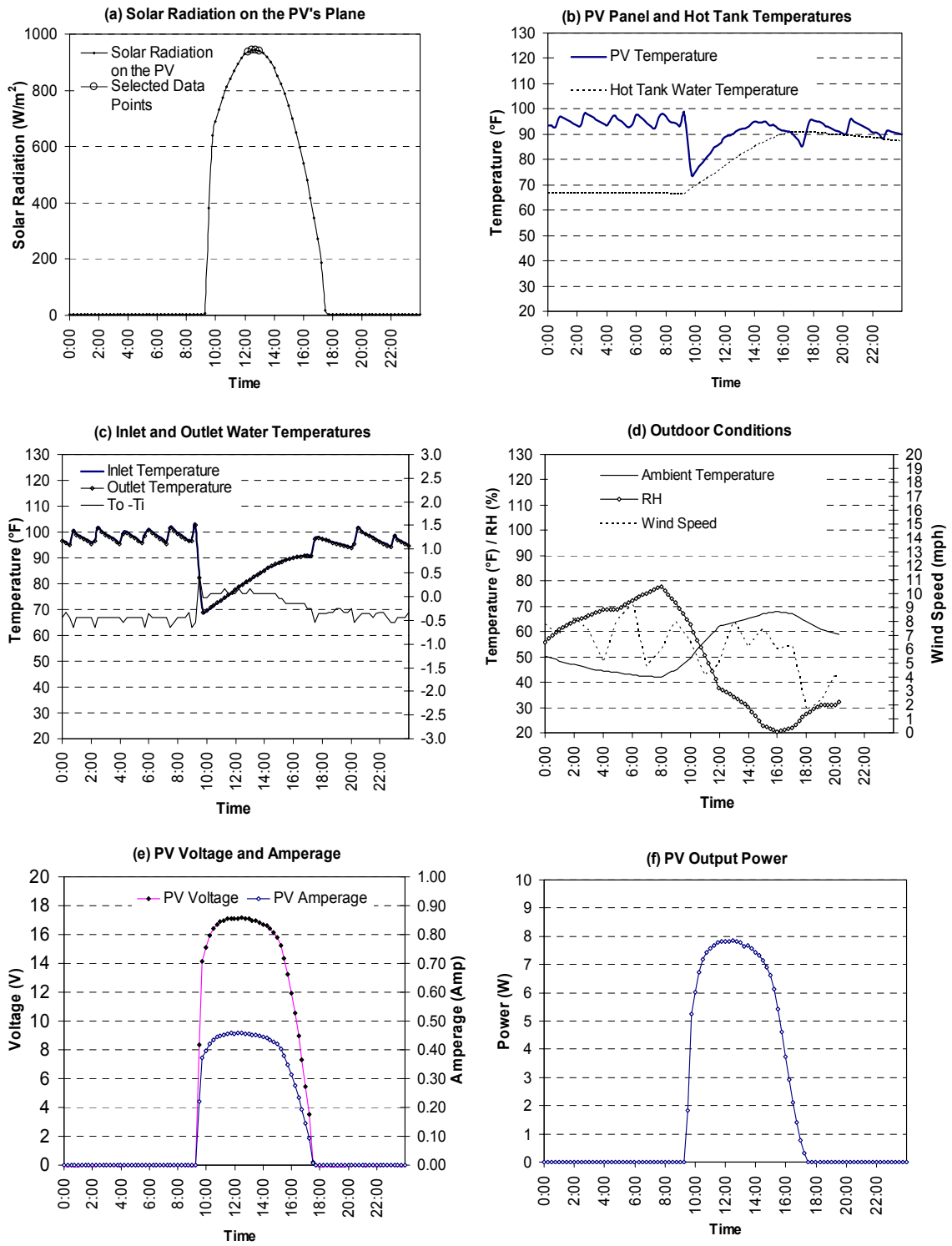


Figure 6.5 *Electrical Energy Output and Conditions of the Hybrid PV-T² Experiments for the Dec 20, 2002 experiment.*

TABLE 6.2

Measured Data and Results from the Photovoltaic System

Date	T_p (°F)	T_p (°C)	I_t (W/sq.m)	$I_t \cdot A_g$ (W)	PV Electrical Output Voltage (V)	Ampare (A)	Power (W)	T_a (°F)	RH (%)	Wind Spd. mph	PV Array Efficiency (η) (Fraction of 0 to 1)	PV Array Efficiency (η) (%)
12/20/02 12:15 PM	89.71	32.06	937.01	92.76	17.14	0.46	7.83	62.44	36.98	5.71	0.0844	8.44
12/20/02 12:30 PM	89.91	32.17	942.16	93.27	17.17	0.46	7.86	62.77	36.10	6.47	0.0843	8.43
12/20/02 12:45 PM	91.21	32.90	942.90	93.35	17.12	0.46	7.82	63.11	35.21	7.24	0.0838	8.38
12/20/02 1:00 PM	91.82	33.23	939.22	92.98	17.09	0.46	7.79	63.45	34.33	8.00	0.0838	8.38
1/6/02 12:15 PM	97.63	36.46	894.28	88.53	16.73	0.45	7.45	65.06	42.09	8.69	0.0841	8.41
1/6/02 12:30 PM	98.83	37.13	904.60	89.56	16.72	0.45	7.44	66.32	40.28	8.13	0.0831	8.31
1/6/02 12:45 PM	99.83	37.68	904.60	89.56	16.69	0.44	7.41	67.58	38.46	7.56	0.0828	8.28
1/6/02 1:00 PM	100.33	37.96	902.39	89.34	16.67	0.44	7.39	68.84	36.65	7.00	0.0827	8.27
1/16/03 1:30 PM	52.20	11.22	932.59	92.33	17.89	0.48	8.66	53.70	35.44	14.91	0.0938	9.38
1/16/03 1:45 PM	51.96	11.09	915.65	90.65	17.82	0.48	8.58	53.86	35.19	14.99	0.0947	9.47
1/16/03 2:00 PM	51.63	10.90	892.81	88.39	17.72	0.48	8.46	54.02	34.94	15.06	0.0958	9.58
1/16/03 2:15 PM	51.22	10.68	864.82	85.62	17.55	0.47	8.29	54.02	34.69	15.16	0.0968	9.68
												0.00
5/31/03 1:30 PM	121.57	49.76	892.08	88.32	15.87	0.42	6.68	101.66	32.09	1.93	0.0756	7.56
5/31/03 1:45 PM	122.07	50.04	896.49	88.75	15.86	0.42	6.67	102.32	31.32	2.06	0.0752	7.52
5/31/03 2:00 PM	123.88	51.04	896.49	88.75	15.75	0.42	6.59	102.97	30.55	2.19	0.0742	7.42
5/31/03 2:15 PM	123.98	51.10	889.87	88.10	15.66	0.42	6.50	103.06	30.50	2.66	0.0738	7.38
6/7/03 1:30 PM	121.17	49.54	906.81	89.77	15.75	0.42	6.66	96.46	34.94	1.90	0.0742	7.42
6/7/03 1:45 PM	121.77	49.87	907.54	89.85	15.74	0.42	6.64	97.24	34.31	1.67	0.0739	7.39
6/7/03 2:00 PM	122.27	50.15	907.54	89.85	15.75	0.42	6.64	98.03	33.68	1.44	0.0739	7.39
6/7/03 2:15 PM	122.57	50.32	903.86	89.48	15.72	0.42	6.61	98.72	32.97	1.51	0.0739	7.39

The experiments conducted on December 20, 2002, and January 6, 2003, were performed in relatively cool weather conditions; the temperatures on these two days ranged from 62 to 68 °F, and the wind speeds ranged from 5.7 to 8.7 mph (see Table 6.2). On these days the PV panel's temperatures at solar noon were in the range from 89 to 100 °F. These conditions resulted in relatively high power outputs at the solar noon (7.6 watts) each day.

The experiment conducted on January 16, 2003, was performed with the coldest conditions and was the windiest of the five experimental days. The ambient temperature at solar noon was approximately 54 °F, and the wind speed was 15 mph. The experiment conducted on January 16, 2003, was intended to test the thermal and electrical outputs when the PV was very cold. As mentioned in Section 6.1, ice was put into the hot tank to lower the inlet water temperature and the PV temperature. As a result the PV panel's temperature was much lower than the other four experimental days. The average PV temperature at solar noon was 51.7 °F. These conditions resulted in the highest power output measured during the five experimental days which was 8.5 watts (9.53 % efficiency).

PV panel efficiencies were calculated from the five-day data of the PV's power output and solar radiation on the PV's plane. The PV array efficiencies and the PV panel temperatures recorded in Table 6.2 were later used to calculate an array temperature coefficient discussed in the next section.

6.2.2 Electrical Performance of the Hybrid PV-T^2 System

This section discusses the determination of the array temperature coefficient, which is the rate at which the array efficiency linearly decreases with the PV panel's temperature. This coefficient is required for the PV F-Chart program to analyze the electrical performance of the Hybrid PV-T^2 system presented in Chapter VIII.

The results of the PV panel's efficiency measurements discussed in the previous section were plotted against the PV panel's temperatures as shown in Figure 6.6. To calculate the array temperature coefficient a linear regression was performed as shown. Figure 6.6 shows that the PV panel's efficiency decreases as the PV panel temperature increases. Hence, the lower the temperature of the PV panel, the greater the efficiency. The slope of the line is the rate at which the array efficiency decreases with the PV panel's temperature. From the equation outlined in Figure 6.6, the efficiency decreased at the rate of 0.0005 per degree Celsius. This value is the array temperature coefficient of the Hybrid PV- T^2 collector, which was later used for the system input parameter in the PV F-Chart program to analyze the electrical performance of the Hybrid PV- T^2 system.

There is a disagreement between the measured PV panel's electrical efficiency and the rated efficiency by the PV manufacture (Solarex). The manufacture tested PV panels in a solar simulator at Standard Test Conditions (STC) which are illumination of 1 kW/m^2 and cell temperature of 25 ºC (Solarex, 1999). The listed maximum power of the PV panel used in this experiment at STC is 10 W (Solarex, 1999). This yields the efficiency of 10 percent (the surface area of the PV panel is 0.1 m^2). From the results of the measured PV panel's efficiency presented in Figure 6.6, the efficiency is about 8.7 percent at the panel temperature of 25 ºC (the cell temperature was assumed to be close to the panel temperature). The difference of the rated efficiency by the manufacture and the measured efficiency could be due to a couple of factors. First, in this study, the PV panel was analyzed under the real weather condition that could not be controlled. An important factor was the solar radiation on the experiment days which was lower than 1 kW/m^2 as specified in the STC. Second, the PV industry including research

institutions and manufactures use sophisticated and expensive devices called I-V curve tracers to determine the efficiency of a PV panel. This device could accurately measure the maximum power output of a PV panel. However, this device was not used in this research because of its availability and cost. This study used a series of resistors as a load of the PV system. This fixed resistors limited the measurement of maximum power of the PV panel. Thus, the measured PV output in most likely below the maximum power that could produce by the PV panel using an I-V curve tracer. These two factors contributed significantly to the efficiency of the PV. Therefore, because of these measurements, this research assumes that the maximum PV output is approximately 10 percent.

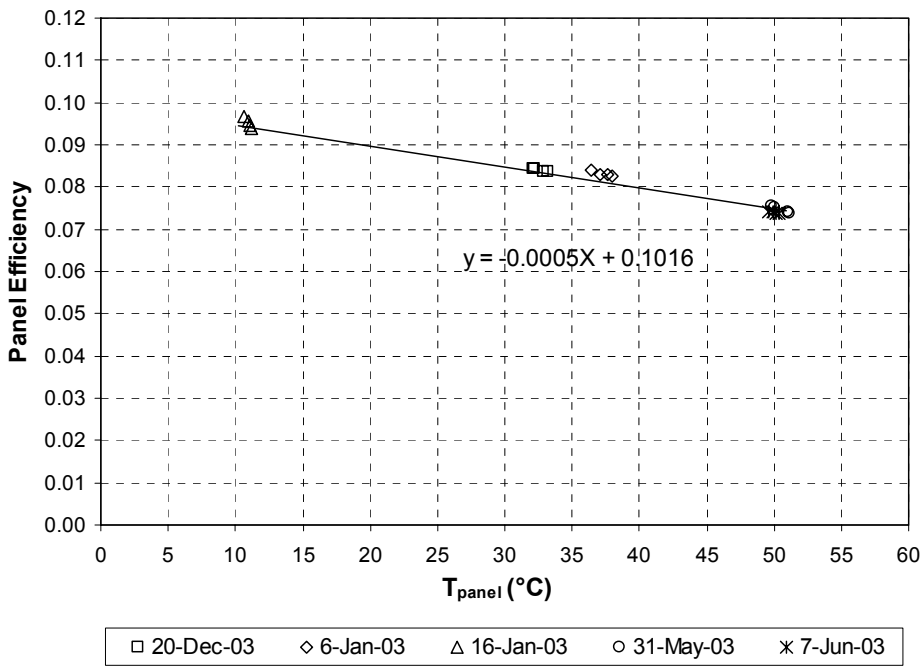


Figure 6.6 *Relationship Between the PV Panel's Efficiency and PV Panel's Temperature.*

6.3 Experimental Case 3: Night Sky Cooling Strategy

The night sky cooling strategy using the PV-T^2 collector was tested in the night mode experiment, which was performed over several evenings. Twelve nights of the night mode experiments were selected for inclusion in the analysis of the heat rejection performance of the

collector. One night of measured data and the results of the heat rejection analysis are presented in Figure 6.7, in Section 6.3.1. The measured data and the results from all the remaining experiments are presented in Appendix B.

A theoretical heat rejection for each night of the night mode experiments was also calculated using equations found in a solar engineering text book (Duffie and Beckman, 1991). The theoretical heat rejection consists of calculations of convective heat loss and radiative heat loss. These calculations are presented in Section 6.3.2. The purpose of these theoretical calculations was to compare the theoretical results with the experimental results.

6.3.1 Results from the Heat Rejection Experiment

Figure 6.7 presents the measured data and the results of the analysis of the night mode experiment of the hybrid PV-T^2 system conducted on May 3-4, 2003. In Figure 6.7, Graph (a) shows the surface temperatures of the PV panel and weather data, including ambient temperature, relative humidity, dew point temperature, and the sky temperature. Graph (b) shows the wind speed and the convection coefficient. Graph (c) shows the results of the experimental and theoretical heat rejection rate. This section discusses only the experimental results. The theoretical results are discussed in the next section.

The heat rejection experiment began at 9:00 p.m. on May 3, 2003 and ended the next morning at 6:00 a.m. As described in the methodology, water in the cool tank was heated by the water heater prior to the experiment. Before the experiment began, the cool tank water temperature was approximately 137 °F (see Table 6.3). When the system was turned to the night mode experiment at 8:15 p.m., the water temperature dropped to 133 °F. This was due to the fact that the relatively cool water existing in the pipe drained back to the cool tank and mixed with the heated water. Thus, it quickly lowered the temperature of the water. The measured data from this beginning period was not used for heat rejection calculations, since the sudden dropping of the water temperature in the cool tank was not due to heat being rejected by the PV panel, but was instead due to the mixing of the waters. Therefore, the measured data for the heat rejection calculations began approximately 30 minutes after the system was turned to the night mode.

Air temperature and dew-point temperatures varied slightly during the experiment night. The ambient temperature was 81°F when the experiment began at 9:00 a.m., and gradually dropped during the night to its lowest point at 74.5°F (from 2:00 a.m. to 3:00 a.m.). Dew-point temperatures also varied a small amount (75.6 °F to 72.3 °F). These conditions resulted in a small change of the estimated sky temperature during the night; the sky temperature varied between 67 °F and 58 °F. While there was only a small change in the ambient temperature and dew-point temperature during the night, the wind speed changed considerably [see Graph (b)]. The wind speed was approximately 3 mph at 9:00 p.m. and had continuously increased to a high of 10.4 mph at 3:00 a.m. Although the wind speed had changed during the night, the convective surface coefficient (h_{cv}) changed very little, especially during the relatively high wind speeds (from 6 to 10 mph). These weather conditions and PV surface temperatures affected the heat rejection rates of the PV panel. The relationship between these variables and the heat rejection rates are presented in Section 6.3.4.

Graph (c) shows the experimental results for the two heat rejection rates, which were calculated by two different methods: 1) calculation of the heat loss (rejected) from the system by calculating the temperature change in the cool tank, and 2) calculation of the heat rejection rate by the difference between the inlet and outlet water temperatures. The results of the two methods show the similarities and differences between the heat rejection rates.

The highest heat rejection rates occurred immediately after beginning the experiment when, the temperature difference between the PV surface and the sky was at its highest. The significant temperature differences were largely due to the high temperature of the PV surface, since the ambient and sky temperatures changed very little, and the wind speed was very low (less than 3 mph). From Graph (c), it can be noticed that the heat rejection rates from both calculation methods are relatively similar near the beginning of the experiment to 10:30 p.m. After that the differences between the results become greater. There are similar results from night mode experiments which are presented in Appendix B. The lowest heat rejection rates from both methods occurred in the morning, between 5 and 6 a.m., when temperature differences between the PV surface and the sky, and between the PV surface and the ambient air were the smallest (a 30 °F difference and a 13.4 °F difference respectively).

Experimental results were compared to the results from the theoretical calculations as shown in Figure 6.7. The theoretical results are presented and discussed in the next chapter. Comparisons of the results are discussed in Section 6.3.3.

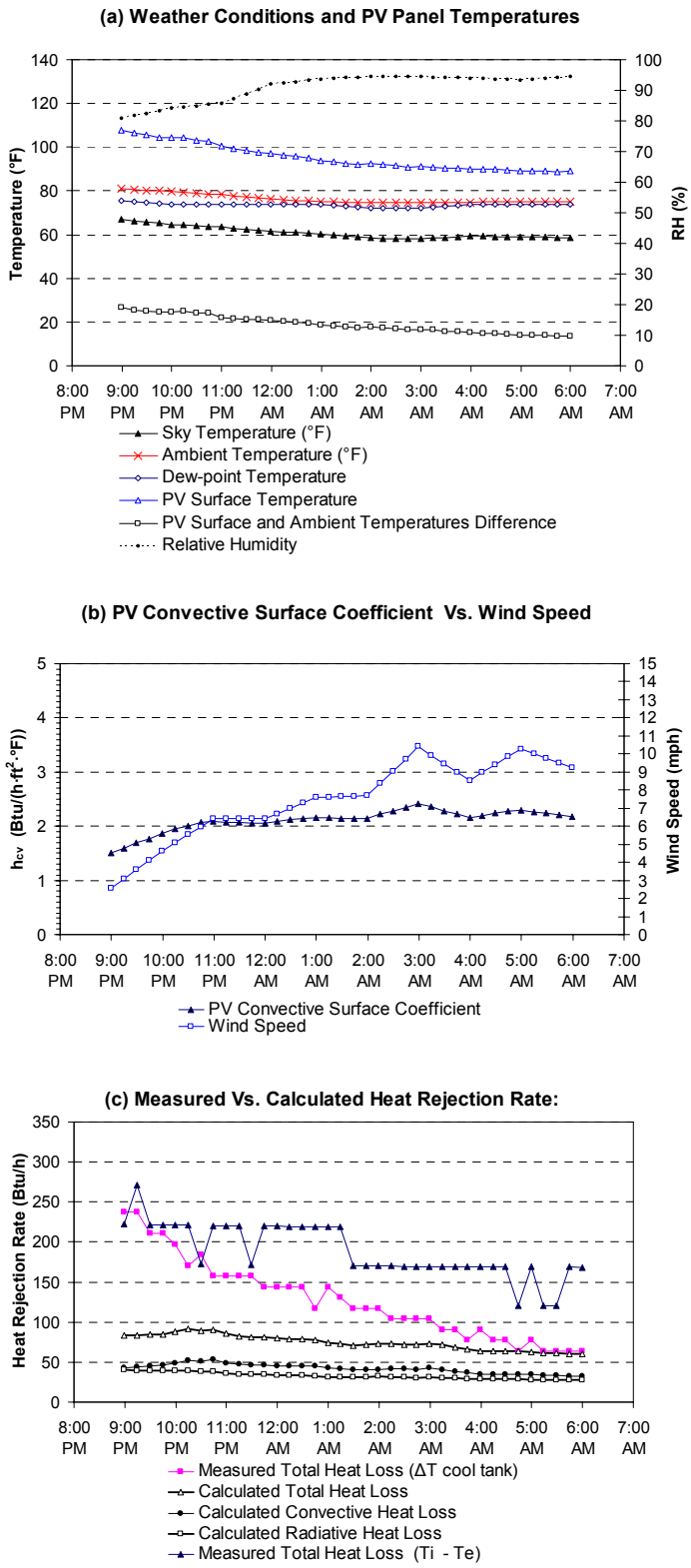


Figure 6.7 *Results from the Night Mode Experiment Conducted on May 3-4, 2003.*

6.3.2 Results from Theoretical Heat Rejection Calculations

Theoretical heat rejection consists of calculations using convective and radiative heat losses presented in Chapter IV. The total heat rejection rate is presented in Graph (c) in Figure 6.7. Results from the convective heat loss calculations are presented in Section 6.3.2.1, and the results from the radiative heat loss calculations are presented in Section 6.3.2.2.

6.3.2.1 Results from Convective Heat Loss Calculations

Table 6.4 shows the weather data, measured data, and results from the convective heat loss calculation conducted on May 3-4, 2003. The weather data used in the calculation includes the ambient temperature and the wind speed. The surface temperature of the PV was the only measured data from the experimental box used in the convective heat loss calculation. Constants and parameters used in the calculation, which are not shown on Table 6.4, are presented in Chapter IV, Section 4.2.4.3. The convective heat loss rates shown on Table 6.4 were plotted on Figure 6.7, Graph (c), so that they might be compared with the experimental results.

From equations 4.6 and 4.7, the ambient temperature, PV surface temperature, and wind speeds are seen to be key parameters in determining the convective heat loss rate. From Table 6.4, it can be seen that the convective heat loss rates ranged from 32 to 56 Btu/h-ft^2. Figure 6.6 shows that high convective heat loss rates occurred when the difference of the PV surface temperature and ambient temperature was large, which was between 10:15 p.m. and 10:45 p.m. The effect of the wind speed can be seen during this period. In this period, the temperature difference between the PV surface and the ambient air was at approximately the same, since the experiment began at 9:00 p.m. However, the wind speed was nearly two times higher (i.e., the wind speed increased from 2.6 to 6 mph between 9:00 p.m. and 11:00 p.m. Convective heat loss decreased after this period and reached its lowest rate when the experiment was ended at 6:00 a.m., even though the wind speed had considerably increased during the night.

TABLE 6.3

Measured Data and Results of the Heat Rejection Experiment Conducted on May 3-4, 2003

Date	Measured Data from the Experiment Box							Heat Rejection Calculation Method 1 (using ΔT_c)				Heat Rejection Calculation Method 2 (using $T_{f,e}$-$T_{f,i}$)	
	T_P (°F)	$T_{f,i}$ (°F)	$T_{f,e}$ (°F)	T_c (°F)	T_{sur} (°F)	$T_{f,e}$-$T_{f,i}$ (°F Diff.)	ΔT_c (°F Diff.)	Q_c (Btu)	ΔQ_c (Btu)	Q_{rej-1} (Btu/15 min)	Q_{rej-1} (Btu/h)	Q_{rej-2} Btu/15 min	Q_{rej-2} Btu/h
*5/3/2003 8:00:00	81.70	94.59	92.94	137.16	81.93	-1.65	0.40	4575.66	13.36	19.29	77.18	199.84	799.37
*5/3/2003 8:15:00	108.95	128.35	126.89	132.86	99.66	-1.46	4.30	4432.06	143.59	149.53	598.11	177.18	708.73
*5/3/2003 8:30:00	117.56	130.25	129.79	130.25	110.67	-0.46	2.60	4345.24	86.82	92.76	371.04	55.77	223.08
*5/3/2003 8:45:00	117.36	128.55	128.09	128.55	111.27	-0.46	1.70	4288.47	56.77	62.71	250.82	55.69	222.75
5/3/03 9:00 PM	114.66	126.95	126.49	126.95	107.87	-0.46	1.60	4235.04	53.43	59.37	237.47	55.61	222.44
5/3/03 9:15 PM	113.16	125.44	124.89	125.35	106.37	-0.56	1.60	4181.61	53.43	59.37	237.47	67.69	270.75
5/3/03 9:30 PM	112.15	123.94	123.48	123.95	105.46	-0.46	1.40	4134.86	46.75	52.69	210.75	55.46	221.86
5/3/03 9:45 PM	110.95	122.64	122.18	122.55	104.46	-0.46	1.40	4088.11	46.75	52.69	210.75	55.40	221.60
5/3/03 10:00 PM	110.35	121.34	120.88	121.24	104.26	-0.46	1.30	4044.70	43.41	49.35	197.39	55.34	221.35
5/3/03 10:15 PM	109.95	120.23	119.78	120.14	104.26	-0.46	1.10	4007.97	36.73	42.67	170.68	55.28	221.14
5/3/03 10:30 PM	108.65	119.03	118.68	118.94	102.96	-0.35	1.20	3967.90	40.07	46.01	184.04	43.08	172.30
5/3/03 10:45 PM	108.05	118.03	117.58	117.94	102.66	-0.45	1.00	3934.50	33.39	39.33	157.32	55.18	220.71
5/3/03 11:00 PM	106.24	117.03	116.58	116.94	100.46	-0.45	1.00	3901.11	33.39	39.33	157.32	55.13	220.51
5/3/03 11:15 PM	105.14	116.03	115.57	115.94	99.26	-0.45	1.00	3867.72	33.39	39.33	157.32	55.08	220.32
5/3/03 11:30 PM	104.24	115.03	114.67	114.94	98.46	-0.35	1.00	3834.32	33.39	39.33	157.32	42.88	171.52
5/3/03 11:45 PM	103.54	114.12	113.67	114.04	97.75	-0.45	0.90	3804.27	30.05	35.99	143.96	54.99	219.95
5/4/03 12:00 AM	102.64	113.22	112.77	113.14	96.95	-0.45	0.90	3774.21	30.05	35.99	143.96	54.94	219.77
5/4/03 12:15 AM	101.83	112.32	111.87	112.24	96.15	-0.45	0.90	3744.16	30.05	35.99	143.96	54.90	219.60
5/4/03 12:30 AM	101.33	111.52	111.07	111.33	95.75	-0.45	0.90	3714.11	30.05	35.99	143.96	54.86	219.44
5/4/03 12:45 AM	100.43	110.72	110.27	110.63	94.95	-0.45	0.70	3690.73	23.38	29.31	117.25	54.82	219.29
5/4/03 1:00 AM	99.33	109.92	109.47	109.73	93.75	-0.45	0.90	3660.68	30.05	35.99	143.96	54.78	219.13
5/4/03 1:15 AM	98.73	109.12	108.66	108.93	93.25	-0.45	0.80	3633.96	26.71	32.65	130.61	54.74	218.97
5/4/03 1:30 AM	98.03	108.31	107.96	108.23	92.45	-0.35	0.70	3610.59	23.38	29.31	117.25	42.55	170.22
5/4/03 1:45 AM	97.53	107.61	107.26	107.53	92.25	-0.35	0.70	3587.21	23.38	29.31	117.25	42.52	170.08
5/4/03 2:00 AM	97.43	106.91	106.56	106.83	92.35	-0.35	0.70	3563.84	23.38	29.31	117.25	42.49	169.94
5/4/03 2:15 AM	96.92	106.31	105.96	106.23	91.95	-0.35	0.60	3543.80	20.04	25.97	103.89	42.46	169.83
5/4/03 2:30 AM	96.32	105.71	105.36	105.63	91.45	-0.35	0.60	3523.76	20.04	25.97	103.89	42.43	169.71
5/4/03 2:45 AM	95.82	105.11	104.76	105.03	90.95	-0.35	0.60	3503.73	20.04	25.97	103.89	42.40	169.59
5/4/03 3:00 AM	95.72	104.51	104.16	104.43	91.05	-0.35	0.60	3483.69	20.04	25.97	103.89	42.37	169.48
5/4/03 3:15 AM	95.52	104.11	103.76	103.93	90.95	-0.35	0.50	3467.00	16.70	22.63	90.53	42.35	169.40
5/4/03 3:30 AM	95.02	103.61	103.26	103.43	90.45	-0.35	0.50	3450.30	16.70	22.63	90.53	42.33	169.30
5/4/03 3:45 AM	94.82	103.11	102.76	103.03	90.35	-0.35	0.40	3436.94	13.36	19.29	77.18	42.30	169.20
5/4/03 4:00 AM	94.32	102.71	102.36	102.53	89.94	-0.35	0.50	3420.24	16.70	22.63	90.53	42.28	169.13
5/4/03 4:15 AM	94.22	102.30	101.96	102.12	89.94	-0.35	0.40	3406.89	13.36	19.29	77.18	42.26	169.05
5/4/03 4:30 AM	93.92	101.90	101.56	101.72	89.74	-0.35	0.40	3393.53	13.36	19.29	77.18	42.24	168.97
5/4/03 4:45 AM	93.82	101.50	101.26	101.42	89.64	-0.25	0.30	3383.51	10.02	15.96	63.82	30.07	120.29
5/4/03 5:00 AM	93.32	101.20	100.85	101.02	89.24	-0.35	0.40	3370.15	13.36	19.29	77.18	42.21	168.83
5/4/03 5:15 AM	93.12	100.80	100.55	100.72	89.04	-0.25	0.30	3360.14	10.02	15.96	63.82	30.04	120.15
5/4/03 5:30 AM	93.12	100.50	100.25	100.42	89.14	-0.25	0.30	3350.12	10.02	15.96	63.82	30.02	120.10
5/4/03 5:45 AM	92.82	100.30	99.95	100.12	88.84	-0.35	0.30	3340.10	10.02	15.96	63.82	42.16	168.66
5/4/03 6:00 AM	92.72	100.00	99.65	99.82	88.94	-0.35	0.30	3330.08	10.02	15.96	63.82	42.15	168.60

* Data was not used in the heat rejection analysis

TABLE 6.4

Measured Data and the Results of Heat Convection Calculation Conducted on May 3-4, 2003

Date	T_a (°F)	T_a (°R)	RH (%)	T_{sur} (°F)	T_{sur} (°R)	$\Delta T = T_{sur} - T_a$ (°R)	T_{avg}* (°F)	T_{avg} (°R)	Wind Spd. (mph)	h_{cv} Btu/(h·ft$_2$·°F)	Q_{cv} Btu/h
5/3/03 9:00 PM	81.14	540.81	80.99	107.87	567.54	26.73	94.50	554.17	2.59	1.503	42.80
5/3/03 9:15 PM	80.76	540.43	81.77	106.37	566.04	25.61	93.56	553.23	3.10	1.595	43.49
5/3/03 9:30 PM	80.38	540.05	82.55	105.46	565.13	25.09	92.92	552.59	3.61	1.687	45.07
5/3/03 9:45 PM	79.99	539.66	83.33	104.46	564.13	24.47	92.23	551.90	4.11	1.770	46.12
5/3/03 10:00 PM	79.61	539.28	84.11	104.26	563.93	24.65	91.94	551.61	4.62	1.863	48.91
5/3/03 10:15 PM	79.30	538.97	84.51	104.26	563.93	24.96	91.78	551.45	5.07	1.946	51.74
5/3/03 10:30 PM	78.98	538.65	84.92	102.96	562.63	23.98	90.97	550.64	5.52	1.998	51.03
5/3/03 10:45 PM	78.67	538.34	85.32	102.66	562.33	23.99	90.67	550.34	5.97	2.069	52.87
5/3/03 11:00 PM	78.36	538.03	85.72	100.46	560.13	22.10	89.41	549.08	6.42	2.092	49.24
5/3/03 11:15 PM	77.82	537.49	87.28	99.26	558.93	21.44	88.54	548.21	6.42	2.075	47.37
5/3/03 11:30 PM	77.28	536.95	88.85	98.46	558.13	21.18	87.87	547.54	6.41	2.067	46.63
5/3/03 11:45 PM	76.74	536.41	90.41	97.75	557.42	21.02	87.25	546.92	6.41	2.063	46.17
5/4/03 12:00 AM	76.20	535.87	91.97	96.95	556.62	20.75	86.58	546.25	6.40	2.055	45.43
5/4/03 12:15 AM	75.93	535.60	92.40	96.15	555.82	20.22	86.04	545.71	6.70	2.084	44.88
5/4/03 12:30 AM	75.66	535.33	92.83	95.75	555.42	20.09	85.71	545.38	7.00	2.122	45.40
5/4/03 12:45 AM	75.39	535.06	93.25	94.95	554.62	19.56	85.17	544.84	7.30	2.148	44.74
5/4/03 1:00 AM	75.12	534.79	93.68	93.75	553.42	18.63	84.44	544.11	7.60	2.159	42.84
5/4/03 1:15 AM	74.97	534.64	93.91	93.25	552.92	18.28	84.11	543.78	7.63	2.152	41.91
5/4/03 1:30 AM	74.81	534.48	94.14	92.45	552.12	17.64	83.63	543.30	7.65	2.135	40.11
5/4/03 1:45 AM	74.65	534.32	94.36	92.25	551.92	17.60	83.45	543.12	7.68	2.137	40.05
5/4/03 2:00 AM	74.49	534.16	94.59	92.35	552.02	17.85	83.42	543.09	7.70	2.149	40.85
5/4/03 2:15 AM	74.49	534.16	94.56	91.95	551.62	17.45	83.22	542.89	8.38	2.219	41.25
5/4/03 2:30 AM	74.49	534.16	94.54	91.45	551.12	16.95	82.97	542.64	9.05	2.282	41.20
5/4/03 2:45 AM	74.49	534.16	94.51	90.95	550.62	16.45	82.72	542.39	9.73	2.341	41.01
5/4/03 3:00 AM	74.49	534.16	94.49	91.05	550.72	16.55	82.77	542.44	10.41	2.419	42.64
5/4/03 3:15 AM	74.58	534.25	94.39	90.95	550.62	16.36	82.76	542.43	9.94	2.360	41.13
5/4/03 3:30 AM	74.67	534.34	94.29	90.45	550.12	15.77	82.56	542.23	9.47	2.286	38.39
5/4/03 3:45 AM	74.76	534.43	94.19	90.35	550.02	15.58	82.55	542.22	9.00	2.225	36.93
5/4/03 4:00 AM	74.85	534.52	94.09	89.94	549.61	15.09	82.40	542.07	8.53	2.153	34.61
5/4/03 4:15 AM	74.94	534.61	93.91	89.94	549.61	15.00	82.44	542.11	8.97	2.200	35.14
5/4/03 4:30 AM	75.03	534.70	93.73	89.74	549.41	14.71	82.39	542.06	9.40	2.237	35.05
5/4/03 4:45 AM	75.12	534.79	93.56	89.64	549.31	14.52	82.38	542.05	9.84	2.277	35.21
5/4/03 5:00 AM	75.21	534.88	93.38	89.24	548.91	14.03	82.23	541.90	10.28	2.302	34.40
5/4/03 5:15 AM	75.21	534.88	93.68	89.04	548.71	13.83	82.13	541.80	10.02	2.267	33.39
5/4/03 5:30 AM	75.21	534.88	93.99	89.14	548.81	13.93	82.18	541.85	9.77	2.244	33.29
5/4/03 5:45 AM	75.21	534.88	94.29	88.84	548.51	13.63	82.03	541.70	9.51	2.204	31.99
5/4/03 6:00 AM	75.21	534.88	94.59	88.94	548.61	13.73	82.08	541.75	9.25	2.180	31.89

* $T_{avg} = (T_a+T_{sur})/2$

In summary, the wind speed had a noticeable effect on the convective heat loss rate. However, the temperature difference between the PV surface and the ambient air mainly determined the magnitude of the rate at which the heat was convectively lost. Effects of the wind and other variables were analyzed using all the collected night mode data (from all twelve nights). The results are presented in section 6.3.4.

6.3.2.2 Results from the Radiative Heat Loss Calculation

Table 6.5 shows the weather data, measured data, and results from the radiative heat loss calculation conducted on May 3-4, 2003. Weather data used in this calculation includes the hourly ambient temperature, relative humidity, and the wind speed. Sky temperatures were calculated from the ambient and dew point temperatures. The surface temperature of the PV was the only measured data from the experimental box used in the radiative heat loss calculation. Constants and parameters used in the calculation which are not shown on Table 6.5 are presented in Chapter IV, Section 4.2.4.3. Radiative heat loss rates shown on Table 6.5 are plotted on Figure 6.7, Graph (c), so that they might be compared to the experimental results.

From equation 4.8, it can be seen that the PV surface temperature and the sky temperature are key parameters for determining the radiative heat loss rate (with a constant surface area). From Table 6.5, the radiative heat loss rates can be seen to range from 28 to 41 Btu/h-ft^2. Figure 6.7 shows that high radiative heat loss rates occurred when the difference between the PV surface temperature and the sky temperature was at its greatest, which occurred at the beginning of the experiment (9:00 p.m.). Radiative heat loss decreased as the temperature difference between the PV surface and the sky decreased, and reached its lowest rate when the experiment ended at 6:00 a.m.

From the results of the radiative and convection heat losses calculated on May 3-4, 2003, it can be seen that both heat loss rates were very similar; radiative heat loss rates were only slightly lower than convective heat loss rates. However, the relative humidity of the experiment night was quite high (i.e., it ranged from 80 to 90 percent), and therefore the calculated sky temperature was relatively warm as compared to the weather conditions of the night mode experiment conducted on April 25-26, 2003 (see the results of this night mode experiment in Appendix B). The high humidity and warm night sky caused the low radiative heat loss rate. During the night mode experiment conducted on April 25-26, 2003, the radiative heat loss rates were higher than the convective heat loss rates. This was also contributed to by the low wind speeds during the night.

The results from the radiative and convective heat losses of May 3-4, 2003, show that the PV surface temperature was the most influential factor in both the radiative and convective heat losses. Wind speed was also a factor that could accelerate the convective heat loss rate, as describe in Section 6.3.2.1.

TABLE 6.5

Measured Data and Results of the Heat Radiation Calculation Conducted on May 3-4, 2003

Date	Measured Data						Sky Temperature Calculation						Radiative Heat Loss		
	T_a (°F)	T_a (K)	T_{sur} (°F)	T_{sur} (K)	Wind (mph)	RH (%)	T_{dp} (°F)	T_{dp} (°C)	t* (Hour)	T_{sky} (K)	T_{sky} (°C)	T_{sky} (°F)	Q_{rad} (Watt)	$Q_{rad,hor}$ (Btu/h)	Q_{rad} (Btu/h)
5/3/03 9:00 PM	81.14	300.45	107.87	315.30	2.59	80.99	75.60	24.22	3.00	292.53	19.38	66.89	12.93	44.13	41.07
5/3/03 9:15 PM	80.76	300.24	106.37	314.46	3.10	81.77	75.20	24.00	2.75	292.21	19.06	66.31	12.57	42.89	39.92
5/3/03 9:30 PM	80.38	300.03	105.46	313.96	3.61	82.55	74.81	23.78	2.50	291.88	18.73	65.72	12.42	42.38	39.45
5/3/03 9:45 PM	79.99	299.81	104.46	313.41	4.11	83.33	74.41	23.56	2.25	291.55	18.40	65.13	12.24	41.76	38.87
5/3/03 10:00 PM	79.61	299.60	104.26	313.30	4.62	84.11	74.01	23.34	2.00	291.22	18.07	64.53	12.34	42.09	39.18
5/3/03 10:15 PM	79.30	299.43	104.26	313.30	5.07	84.51	74.01	23.34	1.75	291.08	17.93	64.28	12.40	42.32	39.39
5/3/03 10:30 PM	78.98	299.25	102.96	312.57	5.52	84.92	74.01	23.34	1.50	290.94	17.79	64.03	12.03	41.03	38.19
5/3/03 10:45 PM	78.67	299.08	102.66	312.41	5.97	85.32	74.01	23.34	1.25	290.80	17.65	63.76	12.00	40.93	38.10
5/3/03 11:00 PM	78.36	298.90	100.46	311.18	6.42	85.72	74.01	23.34	1.00	290.65	17.50	63.49	11.32	38.62	35.95
5/3/03 11:15 PM	77.82	298.60	99.26	310.51	6.42	87.28	74.01	23.34	0.75	290.37	17.22	63.00	11.05	37.71	35.10
5/3/03 11:30 PM	77.28	298.30	98.46	310.07	6.41	88.85	74.01	23.34	0.50	290.09	16.94	62.50	10.92	37.26	34.69
5/3/03 11:45 PM	76.74	298.01	97.75	309.68	6.41	90.41	74.01	23.34	0.25	289.81	16.66	61.98	10.83	36.94	34.39
5/4/03 12:00 AM	76.20	297.71	96.95	309.24	6.40	91.97	74.01	23.34	0.00	289.52	16.37	61.46	10.70	36.52	33.99
5/4/03 12:15 AM	75.93	297.56	96.15	308.79	6.70	92.40	74.01	23.34	0.25	289.37	16.22	61.20	10.51	35.86	33.38
5/4/03 12:30 AM	75.66	297.41	95.75	308.57	7.00	92.83	74.01	23.34	0.50	289.22	16.07	60.92	10.45	35.66	33.19
5/4/03 12:45 AM	75.39	297.26	94.95	308.12	7.30	93.25	74.01	23.34	0.75	289.06	15.91	60.64	10.26	35.02	32.60
5/4/03 1:00 AM	75.12	297.11	93.75	307.46	7.60	93.68	74.01	23.34	1.00	288.90	15.75	60.35	9.95	33.95	31.60
5/4/03 1:15 AM	74.97	297.02	93.25	307.18	7.63	93.91	73.59	23.11	1.25	288.63	15.48	59.86	9.92	33.85	31.51
5/4/03 1:30 AM	74.81	296.93	92.45	306.73	7.65	94.14	73.17	22.87	1.50	288.35	15.20	59.36	9.80	33.42	31.11
5/4/03 1:45 AM	74.65	296.85	92.25	306.62	7.68	94.36	72.75	22.64	1.75	288.07	14.92	58.85	9.87	33.66	31.34
5/4/03 2:00 AM	74.49	296.76	92.35	306.68	7.70	94.59	72.33	22.41	2.00	287.78	14.63	58.34	10.04	34.24	31.87
5/4/03 2:15 AM	74.49	296.76	91.95	306.45	8.38	94.56	72.33	22.41	2.25	287.75	14.60	58.27	9.92	33.86	31.52
5/4/03 2:30 AM	74.49	296.76	91.45	306.18	9.05	94.54	72.33	22.41	2.50	287.70	14.55	58.20	9.78	33.38	31.07
5/4/03 2:45 AM	74.49	296.76	90.95	305.90	9.73	94.51	72.33	22.41	2.75	287.66	14.51	58.12	9.64	32.90	30.62
5/4/03 3:00 AM	74.49	296.76	91.05	305.95	10.41	94.49	72.33	22.41	3.00	287.61	14.46	58.03	9.70	33.09	30.80
5/4/03 3:15 AM	74.58	296.81	90.95	305.90	9.94	94.39	72.75	22.64	3.25	287.78	14.63	58.33	9.59	32.70	30.44
5/4/03 3:30 AM	74.67	296.86	90.45	305.62	9.47	94.29	73.17	22.87	3.50	287.94	14.79	58.63	9.35	31.89	29.68
5/4/03 3:45 AM	74.76	296.91	90.35	305.56	9.00	94.19	73.59	23.11	3.75	288.10	14.95	58.92	9.24	31.51	29.33
5/4/03 4:00 AM	74.85	296.96	89.94	305.34	8.53	94.09	74.01	23.34	4.00	288.26	15.11	59.21	9.03	30.81	28.68
5/4/03 4:15 AM	74.94	297.01	89.94	305.34	8.97	93.91	74.01	23.34	4.25	288.25	15.10	59.18	9.04	30.83	28.70
5/4/03 4:30 AM	75.03	297.06	89.74	305.23	9.40	93.73	74.01	23.34	4.50	288.24	15.09	59.16	8.98	30.64	28.52
5/4/03 4:45 AM	75.12	297.11	89.64	305.17	9.84	93.56	74.01	23.34	4.75	288.22	15.07	59.13	8.96	30.56	28.44
5/4/03 5:00 AM	75.21	297.16	89.24	304.95	10.28	93.38	74.01	23.34	5.00	288.20	15.05	59.10	8.84	30.15	28.06
5/4/03 5:15 AM	75.21	297.16	89.04	304.84	10.02	93.68	74.01	23.34	5.25	288.14	14.99	58.97	8.81	30.04	27.96
5/4/03 5:30 AM	75.21	297.16	89.14	304.90	9.77	93.99	74.01	23.34	5.50	288.07	14.92	58.85	8.87	30.26	28.17
5/4/03 5:45 AM	75.21	297.16	88.84	304.73	9.51	94.29	74.01	23.34	5.75	288.00	14.85	58.73	8.81	30.05	27.97
5/4/03 6:00 AM	75.21	297.16	88.94	304.79	9.25	94.59	74.01	23.34	6.00	287.93	14.78	58.60	8.87	30.28	28.18

* Hours from midnight

6.3.3 Comparisons of Results from the Heat Rejection Experiment and the Theoretical Calculations

The results of the night mode experiment conducted on May 3-4, 2003, were presented and discussed in the previous sections. This has shown that the experimental results do not agree with the theoretical results. The experimental results from all twelve experiment nights, presented in Appendix B, are similar to the results of the May 3-4, 2003 experiment; the theory predicts lower heat rejection rates as compared to the experimental results. The next section will discuss the variables and their influences on the heat rejection rates. As discussed in Section 6.3.1, the results of heat rejection rate calculated by the temperature change in the cool tank (method 1) were closer to the theoretical results than the results from method 2. Thus, the results of heat rejection rate that calculated by method 1 were chosen to further investigate

relationships between the heat rejection rate and three dependent variables in the next section. Differences between the experimental and the theoretical results are also rendered in the following sections.

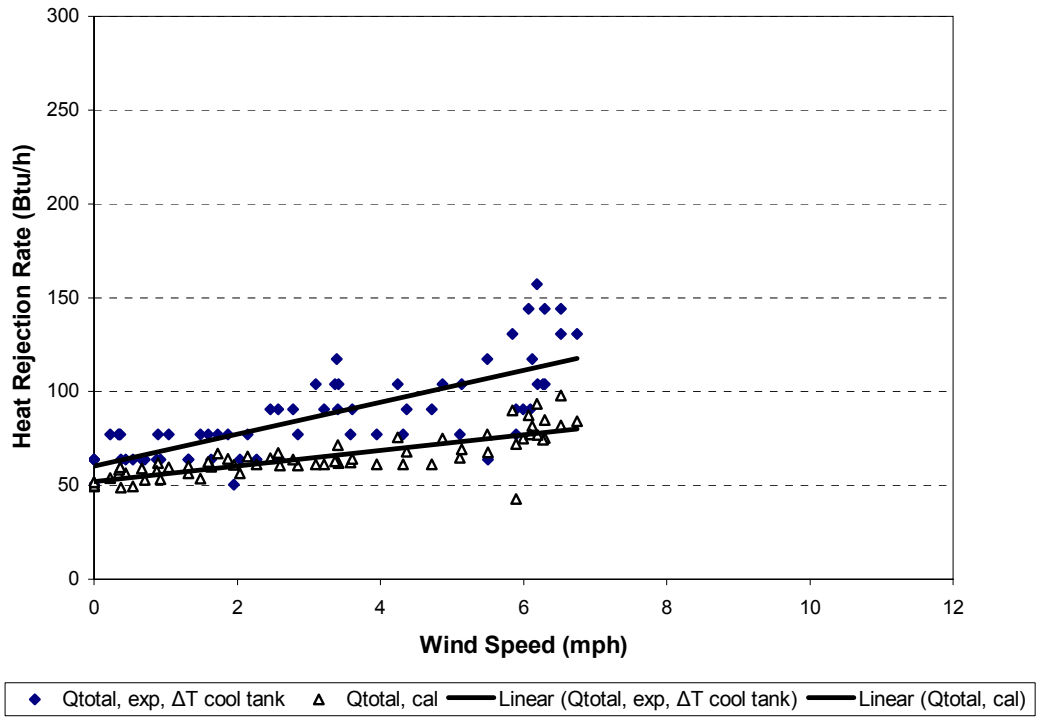
6.3.4 Heat Rejection and Dependent Variables

From the experimental and theoretical results of the heat rejections, it was found that there were four variables that affected the heat rejection rates: 1) the wind speed, 2) the surface temperature of the PV panel, 3) the ambient temperature, and 4) the sky temperature. The following sections present the plotted data of both the experimental and the theoretical heat rejection rates, versus each of those variables or the relationship between those variables.

6.3.4.1 Dependent Variable 1: Wind Speed

Unfortunately there are several variables that simultaneously affect the heat rejection rate. Therefore, to see wind speeds affect on the heat rejection rate, other variables needed to be controlled or limited to a certain range. Thus, experimental and theoretical results from the twelve nights were sorted according to ambient, dew-point, and PV surface temperatures, using a 10 °F range for the various wind speeds. Limited ranges of the variables, as well as the plot of the sorted results, are shown in Figures 6.8 and 6.9.

From Figure 6.8, it can be seen that as the wind speed increases, both the experimental and the theoretical heat rejection rates increase. Interestingly, the experimental and theoretical results are very close when there is no wind (i.e., low wind speeds at 0-2 mph). However, there are still some discrepancies between the two results. First, in general, the experimental results show a higher heat rejection rate than the theoretical at any given wind speed. Second, the experimental heat rejection rate appears to increase at a higher rate as the wind speed increases.

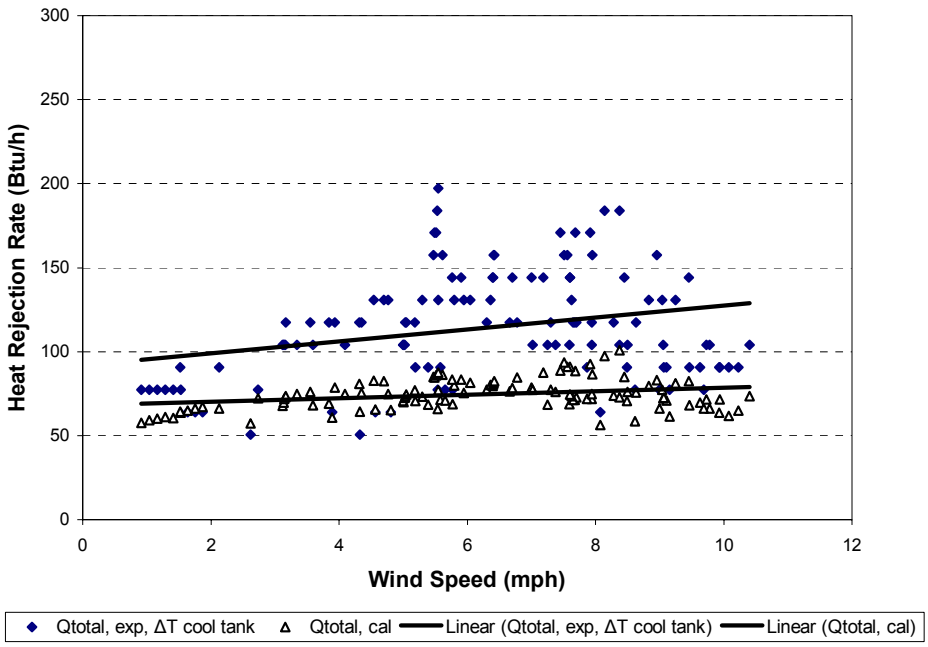


Constants	T_a (° F)	60 to 70	° F
	T_{dp} (° F)	60 to 70	° F
	T_{sur} (° F)	80 to 90	° F
Variables	Wind Speed	Vary	mph

Figure 6.8 *Plot of Calculated Heat Rejection as Compared to the Experimental Results Versus the Wind Speed. Dry-bulb and dew-point temperatures are between 60 ºF and 70 ºF. The panel's surface temperatures are between 80 ºF and 90 ºF.*

Figure 6.9 shows the results at a higher temperature range of examined variables as compared to the results in Figure 6.8. In this figure the ambient and dew-point temperatures were between 70 and 80 °F, and the PV panel surface temperatures were between 90 and 100 °F. The data in Figure 6.9 show some differences to the results in Figure 6.8. First, the experimental and theoretical results are not as close as those in Figure 6.9 at the lower wind speeds. Second, in general, the experimental results in Figure 6.9 show higher heat rejection rates as compared to the theoretical results at a given wind speed. Third, the experimental heat

rejection rate in Figure 6.9 appears to increase less at a higher wind speeds when compared to the rate in Figure 6.8. The combination of Figure 6.8 and Figure 6.9 would indicate a rapidly rising heat rejection rate from 0-7 mph, and a diminishing rise from 7-10 mph, which is unexpected.



Constants	T_a (° F)	70 to 80	° F
	T_{dp} (° F)	70 to 80	° F
	T_{sur} (° F)	90 to 100	° F
Variables	Wind Speed	Vary	mph

Figure 6.9 *Plot of Calculated Heat Rejection as Compared to the Experimental Results Versus Wind Speed. Dry-bulb and dew-point temperatures are between 70 ºF and 80 ºF and the Panel's surface temperatures are between 90 ºF and 100 ºF.*

The results from both Figures 6.8 and 6.9 indicate that the theory under-predicts the heat rejection rate of the experimental panel. Finally, it appears that additional tests are needed to further characterize the panel performance.

6.3.4.2 Dependent Variable 2: Difference between PV Surface Temperature and the Ambient Temperature ($T_{sur} - T_a$)

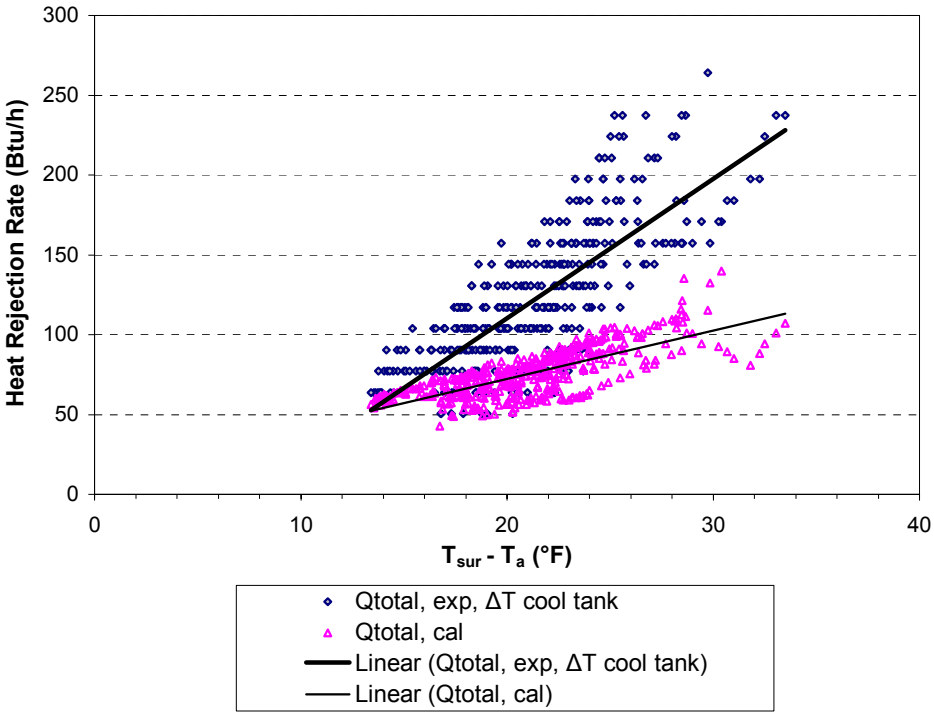
All experimental and theoretical results from the twelve nights were used to analyze the effect of the temperature difference between the ambient air and the PV panel's surface temperature to heat rejection rate. Thus, there were no controlled variables, and each variable was analyzed in a specific range.

In Figure 6.10, the experimental and theoretical results are plotted versus the temperature difference between ambient air and the PV surface. The data from both the experimental and the theoretical results show that the heat rejection rate increases as the temperature difference between the PV panel and the ambient increases. Not surprisingly, the experimental heat rejection rate appears to increase at a higher rate as the temperature difference increases, with the difference between the results becoming greater as the temperature differences increase.

6.3.4.3 Dependent Variable 3: Difference between Surface Temperature and the Sky Temperature ($Tsur^4 - Tsky^4$) ·**d**

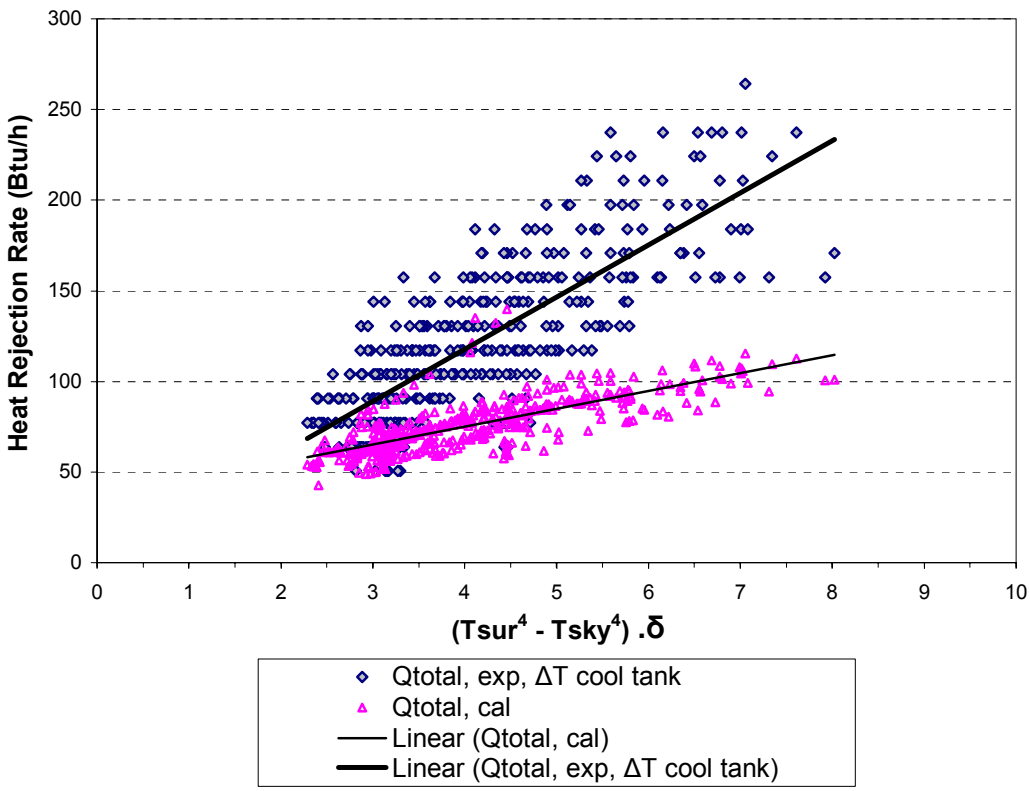
Similar to the analysis of the Dependent Variable 2, all experimental and theoretical results from the twelve nights were used to analyze the effect of the temperature difference between the sky temperature and the PV surface to heat rejection rate. Thus, there were no controlled variables. However, each variable was in a certain range.

In Figure 6.11, the experimental and theoretical results were plotted versus ($Tsur^4$-$Tsky^4$) ·**d,**where **d** is the Stepan-Boltzmann constant = 0.1714 x 10^{-8} Btu/(h · ft^2 ·°R^4). The data from both the experimental and the theoretical results show that the heat rejection rate is well described by the ($Tsur^4$-$Tsky^4$) ·**d** relationship. However, the experimental heat rejection rate appears to increase at a higher rate as the temperature difference increases.



Variables	Range	Min	Max
T_a (° F)	Vary	61.65	84.55
T_{dp} (° F)	Vary	53.81	77.12
T_{sur} (° F)	Vary	80.23	113.28
Wind Speed (mph)	Vary	0.00	11.78

Figure 6.10 *Plot of Calculated Heat Rejection as Compared to the Experimental Results Versus the Difference Between the Panel's Surface Temperature and the Ambient Temperatures. (The ranges of dry-bulb, dew-point, the panel's surface temperatures and the wind speed are varied.)*



Variables	Range	Min	Max
T_a (° F)	Vary	61.65	84.55
T_{dp} (° F)	Vary	53.81	77.12
T_{sur} (° F)	Vary	80.23	113.28
Wind Speed (mph)	Vary	0.00	11.78

Figure 6.11 *Plot of Calculated Heat Rejection as Compared to Experimental Results versus* $(T_{sur}^4 - T_{sky}^4) * \delta$. *(The ranges of ambient, dew-point, panel's surface temperatures and the wind speed are varied.)*

As seen from the plots of theoretical and experimental heat rejection rates, the PV panel could reject heat, which has various heat rejection rates depend on those variables [i.e., wind speed, $(T_{sur} - T_a)$, and $(Tsur^4 - Tsky^4) \cdot \mathbf{d}$]. Since the aim of this research was to conduct experimental study of the heat rejection from a PV panel and compare the experimental results with the theoretical and experimental results. Thus, this research had not made any attempts to adjust the experiment values to reconcile with the theoretical ones.

6.3.5 Multiple Regression Analyses

Regression analyses were performed using a data analysis tool (the add-on analysis tool in Microsoft Excel). All results from the twelve experiment nights were used in this analysis. The three independent variables used in the analysis were the temperature difference between the PV surface and the ambient air, the wind speed, and $(Tsur^4 - Tsky^4) \cdot \mathbf{d}$ relationship. Regression analyses were performed to obtain the mathematical expressions for the predicted heat rejection rate and the predicted water temperature in the cool tank.

6.3.5.1 Multiple Regression Analysis of Heat Rejection Rate

Figure 6.12 presents the measured heat rejection rate, the predicted results, and the difference between the actual and the predicted results. Equation 6.2 was obtained from the regression analysis. It is a model that predicts the heat rejection rate of the whole system, which includes the heat of the pump. In general, the predicted results are reasonably close to the actual temperatures (R^2 is 0.77 and the standard error is 20.90 Btu/hr).

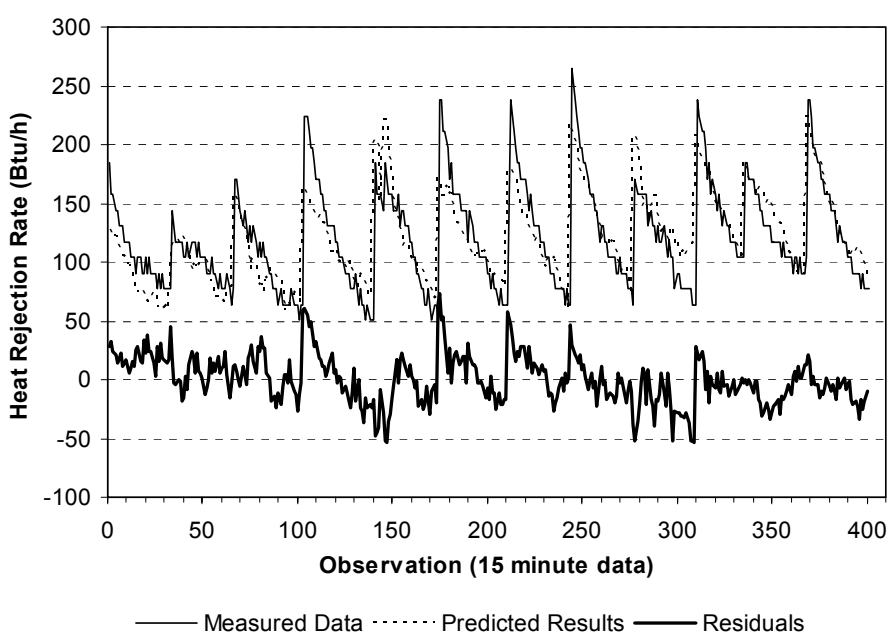


Figure 6.12 *Plot of the Measured and Predicted Heat Rejection Rates.*

$$\dot{Q}_{rej,pred} = -95.15 + 7.22(T_{sur} - T_a) + 5.33(Wind\_Speed) + 9.29((T_{sur}^4 - T_{sky}^4) \cdot \delta) \quad (6.2)$$

where

T_a = Temperature of ambient air (K)
T_{sur} = Temperature of collector surface (K)
T_{sky} = Temperature of sky (K), (Berdahl and Martin, 1984)
d = Stepen-Boltzman constant

6.3.5.2 Multiple Regression Analyses of Water Temperatures in the Cool Tank

Two regression analyses of water temperatures in the cool tank were performed. The first analysis used all the data of the experimented period from all twelve experiment nights to predict the heat loss rate for the whole system (tank + pump). The second analysis used only the last hour of data from each of the experiment nights to predict the final temperature. Figure 6.13 presents the measured cool tank water temperature, the predicted results, and the difference between the actual and the predicted. Equation 6.3 was obtained from the regression analysis. It is a model that predicts the cool tank temperature. From Figure 6.13, it can be seen that the predicted water temperatures were very close to the actual temperatures (R^2 is 0.95 and the standard error is 1.97 ºF).

$$T_{tank,all} = 75.665 + 0.159(T_{sur} - T_a) + 0.670(Wind\_Speed) + 6.486((T_{sur}^4 - T_{sky}^4) \cdot \delta) \quad (6.3)$$

Figure 6.14 presents the last hour of data measured from the cool tank water temperature, the predicted results, and the difference between the actual and the predicted. From Figure 6.14, it can be seen that the predicted water temperatures were very close to the measured data. (R^2 is 0.91 and the standard error is 1.58). Equation 6.4 was obtained from the regression analysis. It is a model that predicts the cool tank temperature for in the last hour of the night mode experiment.

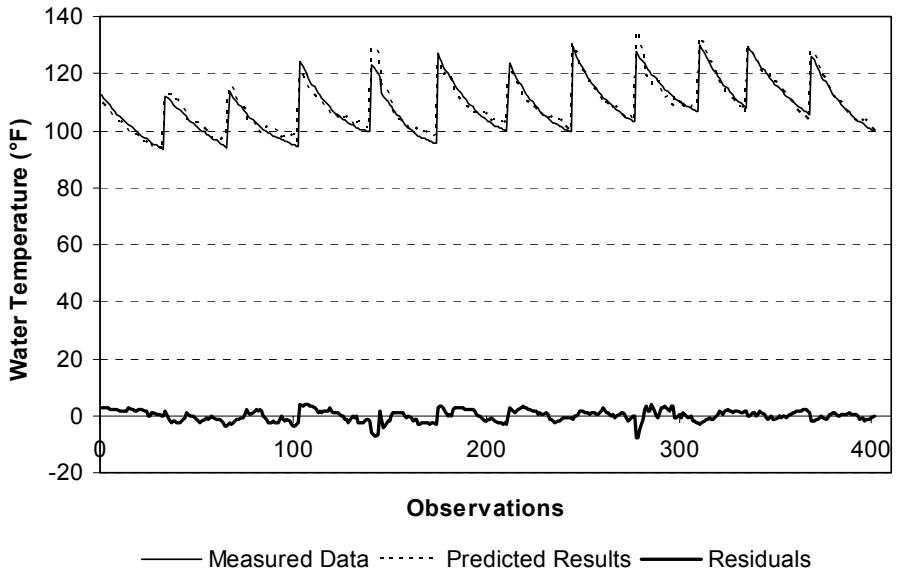


Figure 6.13 *Plot of the Measured and Predicted Water Temperatures in the Cool Tank.*

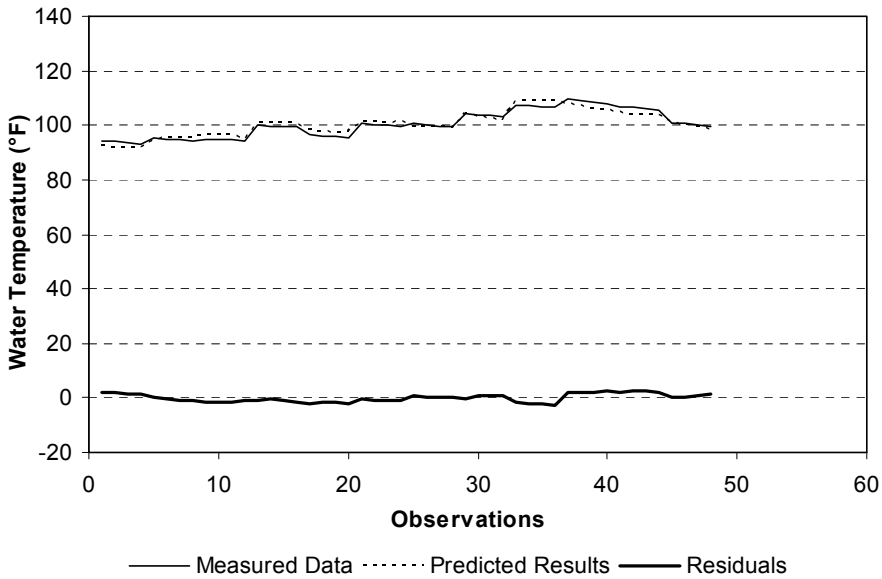


Figure 6.14 *Plot of the Measured and Predicted Water Temperatures in the Cool Tank at the Last Hour of the Experiment Night.*

$$T_{tank,last\_hrs} = 77.395 - 0.248(T_{sur} - T_a) + 0.365(Wind\_Speed) + 8.233((T_{sur}^4 - T_{sky}^4) \cdot \delta)$$

(6.4)

6.4 Total Efficiency of the Hybrid PV-T^2 Collector System

Section 6.1 and 6.2 presented thermal and electrical performance of the hybrid PV-T^2 collector system respectively. This section presents the total collector performance in the day mode experiment of the hybrid PV-T^2 collector system. Total efficiency of a hybrid PV-T collector system (η_{th+e}) is defined as total thermal energy and total electrical energy divided by total insolation over the collector (Garg and Agarwal, 1995). The total efficiency (η_{th+e}), thus, equals to thermal efficiency plus electrical efficiency (as shown in equation 6.5).

$$\eta_{th+e} = \eta_{th} + \eta_e \qquad (6.5)$$

Table 6.6 presents the experimental results of the total efficiency of the hybrid PV-T^2 collector system. Thermal efficiencies were obtained from Table 6.1. Electrical efficiencies were obtained from Table 6.2. Total efficiency of the hybrid PV-T^2 collector system presented in the far right column of Table 6.2 is the result of addition of thermal and electrical efficiencies.

Figure 6.15 presents total efficiency of the hybrid PV-T^2 collector system as a function of $[(t_i-t_a)/I_t]$. As shown in Figure 6.15, the maximum efficiency [when $(t_i-t_a)/I_t = 0$] is approximately 54 percent.

TABLE 6.6

Total Efficiency of the Hybrid PV-T^2 Collector System

DATE TIME	$(t_{f,i}-t_a)/I_t$ °F.Hr.sq.ft/Btu	Efficiency		
		η_{th}	η_e	η_{th+e}
12/20/02 12:15 PM	0.043	0.248	0.0844	0.333
12/20/02 12:30 PM	0.046	0.094	0.0843	0.178
12/20/02 12:45 PM	0.047	0.093	0.0838	0.177
12/20/02 1:00 PM	0.048	0.246	0.0838	0.330
1/6/02 12:15 PM	0.068	0.094	0.0841	0.178
1/6/02 12:30 PM	0.068	0.092	0.0831	0.175
1/6/02 12:45 PM	0.069	0.091	0.0828	0.174
1/6/02 1:00 PM	0.072	0.091	0.0827	0.174
1/16/03 12:30 PM	-0.047	0.736	0.0938	0.830
1/16/03 12:45 PM	-0.039	0.611	0.0947	0.706
1/16/03 1:15 PM	-0.060	0.837	0.0958	0.933
1/16/03 1:30 PM	-0.062	0.849	0.0968	0.946
5/31/03 1:30 PM	0.039	0.161	0.0756	0.237
5/31/03 1:45 PM	0.040	0.160	0.0752	0.236
5/31/03 2:00 PM	0.042	0.321	0.0742	0.395
5/31/03 2:15 PM	0.045	0.162	0.0738	0.235
6/7/03 1:30 PM	0.052	0.159	0.0742	0.233
6/7/03 1:45 PM	0.052	0.158	0.0739	0.232
6/7/03 2:00 PM	0.053	0.158	0.0739	0.232
6/7/03 2:30 PM	0.055	0.162	0.0739	0.235

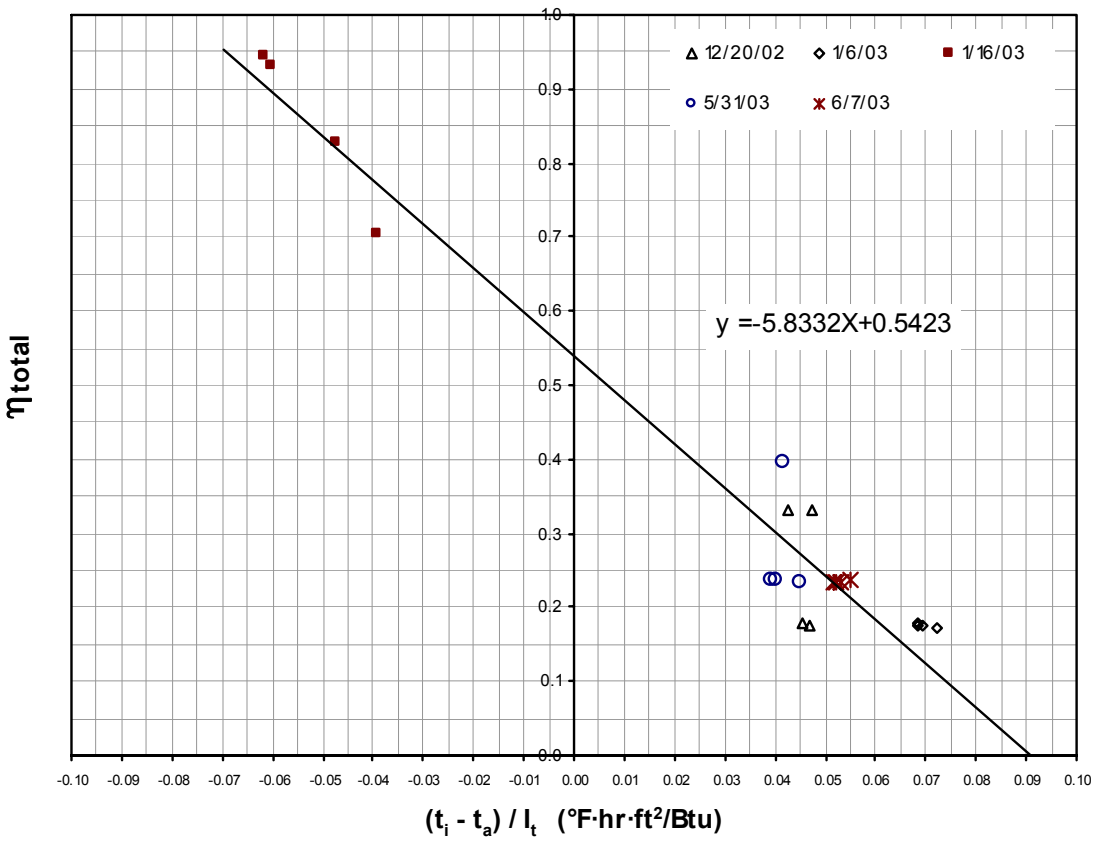


Figure 6.15 *Total Performance of the Hybrid PV-T² System.*

6.5 Summary

This chapter has presented the experimental results from the triple effect hybrid PV-T^2 system. The thermal, electrical, and heat rejection performance of the system was tested and discussed. Selected results are later used in Chapter VII to assess the benefits of this system in a residential application, which was the case-study house. The following is the summary of findings of each effect of the hybrid PV-T^2 system:

1) Thermal Efficiency

- The hybrid PV- T^2 collector system had the maximum thermal efficiency of 45 percent. The measured Test Intercept ($Fr\tau\alpha$) was 0.45 and the measured collector loss coefficient data was -5.6194, which represents FrUL.

- The thermal efficiency of the hybrid PV-T^2 collector system varied significantly with ambient temperature, the thermal efficiency becoming zero at $(t_i - t_a)/I_t > 0.08$.

2) Electrical Efficiency

- The relationship of the PV-T^2 panel's electrical efficiency and panel temperature was reported. The electrical efficiency decreases at the rate of 0.0005 % per one degree Celsius. This value was the array temperature coefficient of the Hybrid PV- T^2 collector, which was later used for the system input parameter in the PV F-Chart program to analyze the electrical performance of the Hybrid PV- T^2 system.

3) Total Efficiency

- Total efficiency, which is the combined thermal and electrical efficiencies, was found from the day mode experiment. The maximum efficiency [when $(t_i - t_a)/I_t = 0$] was approximately 54 percent.

4) Heat Rejection

- The experimental results of heat rejection for the whole system (tank + pump) were presented and compared with the theoretical results. Theoretical heat rejection rates were lower than the experimental results. From the experimental results, relationships between heat rejection rates and three variables [i.e., wind speed, $T_{sur} - T_a$, and $(T_{sur4} - T_{sky4}) * \delta$] were found. A regression analysis of the relationships between the experimental heat rejection rates and those variables was performed and reported. A regression analysis of the relationships between the water temperature in the tank and those variables was also performed and reported.

CHAPTER VII

DATA ANALYSIS AND RESULTS OF BUILDING SIMULATION IN THE DOE-2 WITH THE RESULTS FROM THE F-CHART AND PV-F CHART PROGRAMS

This chapter presents and discusses the results of the simulation of the case-study house which include the calibration of the DOE-2 model against both the measured data and utility bills. This chapter also presents the results of the simulation investigation into energy efficient strategies used to improve the case-study house. There are three main sections presented in this chapter. Section 7.1 presents the results of the first DOE-2 run, Section 7.2 presents the calibration process and the results of the final calibrated model, and Section 7.3 presents the results of the investigation into the energy efficient strategies, as well as supplemental energy provided by the hybrid PV-T^2 collector system, and the photovoltaic system.

7.1 Result of First DOE-2 Run

The first DOE-2 model that ran without errors and gave reasonable results was considered Run # 1. This section presents the results of DOE-2 Run #1 which include both the simulated energy use and the simulated zone temperatures. Simulated energy use is compared to actual energy use in Section 7.1.1. Section 7.1.2 displays the results of the simulated zone temperatures as compared to the measured zone temperatures.

7.1.1 Monthly Energy Use

The monthly electricity bills for the case-study house were obtained from the home-owner. Table 7.1 shows the monthly electricity consumption of the case-study house over a seven month period (from June to December, 2000). Since there were a different number of days in the billing period for each month, the daily average electricity use for each billing period was also calculated. Daily average electricity use is useful when comparing the actual energy use to the simulated use. The simulated energy use was for the calendar month (i.e., the first to the end of the month).

TABLE 7.1

The Case-Study House's Monthly Utility Bills from June to December, 2000

Billing Period			Electricity Bills			
Month	From	To	Number of Days	Electricity Use (kWh)	Avg Elec. Use (kWh/day)	Avg. Outdoor Temp. (°F)
June	29-May-00	28-Jun-00	30	450	15.00	82.48
July	28-Jun-00	28-Jul-00	30	414	13.80	82.48
August	28-Jul-00	29-Aug-00	32	454	14.19	82.96
September	29-Aug-00	28-Sep-00	30	334	11.13	81.62
October	28-Sep-00	28-Oct-00	30	451	15.03	81.65
November	28-Oct-00	28-Nov-00	31	382	12.32	79.51
December	28-Nov-00	28-Dec-00	30	405	13.50	81.03
June to Dec.	29-May-00	28-Dec-00	213	2890	13.57	81.68

TABLE 7.2

Simulated Energy Use Results from the First DOE-2's Run

Month	Lighting (kWh)	Equipment (kWh)	Cooling (kWh)	Vent Fans (kWh)	Energy use (kWh/month)	Period (days)	Avg. Energy use (kWh/day)	Avg. Temp. (°F)
June	27	195	130	16	369	30	12.29	82.43
July	30	206	149	18	403	31	12.99	82.72
August	28	201	155	19	403	31	13.02	82.68
September	28	197	117	14	356	30	11.86	81.46
October	30	206	127	16	379	31	12.22	81.65
November	28	198	110	14	351	30	11.69	79.76
December	29	204	133	16	383	31	12.34	81.00
June to Dec.	200	1408	921	113	2643	214	12.34	81.67

The results of both the simulated monthly and daily average electricity uses are shown in Table 7.2. The comparison of the actual to the simulated daily average electricity uses is presented in Table 7.3. Statistical indices which were used to compare the results of the simulated to the actual data, including the mean bias error (MBE), the root mean squared error (RMSE), and the coefficient of variation for the root mean squared error [CV(RMSE)], are all reported in Table 7.3 as well.

From Table 7.3, the results can be seen to show that the DOE-2 Run # 1 under-predicted the actual monthly energy use by approximately 9 percent (the MBE was -9.03 percent, and the RMSE was 1.67 kWh/day). The CV(RMSE) was 12.33 percent. Figure 7.1, which presents both the actual and the simulated daily electricity uses versus the outdoor

temperature, shows that in general the simulated daily electricity use is lower than the actual average daily electricity use.

TABLE 7.3

Actual Electricity Use vs. Simulated Electricity Use Results from the DOE-2's First Run

Month	Actual Electricity Use (kWh/day)	DOE-2 Simulated Elec. Use (kWh/day)	Error (Simulated-Actual)	Error Square
June	15.00	12.29	-2.71	7.36
July	13.80	12.99	-0.81	0.66
August	14.19	13.02	-1.17	1.37
September	11.13	11.86	0.72	0.52
October	15.03	12.22	-2.82	7.94
November	12.32	11.69	-0.63	0.40
December	13.50	12.34	-1.16	1.34
SUM			-8.58	19.59
			N (months)	7.00
			MBE (%)	-9.03
			RMSE (kWh/day)	1.67
Average	13.57	12.34	CV(RMSE) (%)	12.33

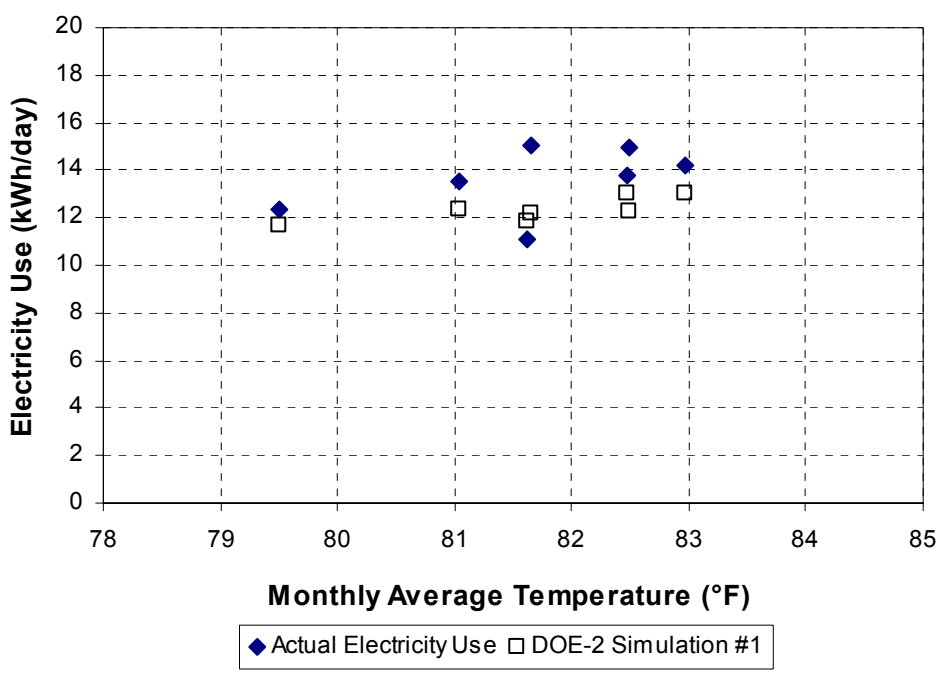


Figure 7.1 *Actual Electricity Use and DOE-2's Run #1 Simulated Energy Use versus the Monthly Average Temperature*

A comparison of the actual to the simulated daily average electricity uses is also presented in a time-series plot in Figure 7.2. Figure 7.2 shows that, in general, the DOE-2 Run# 1 under-predicted the case-study house's daily average electricity use, which corresponds to the results from the statistical index (MBE). A comparison of the actual to the simulated monthly total electricity uses, shown in Figure 7.3, shows similar results to the comparison of the daily electricity uses.

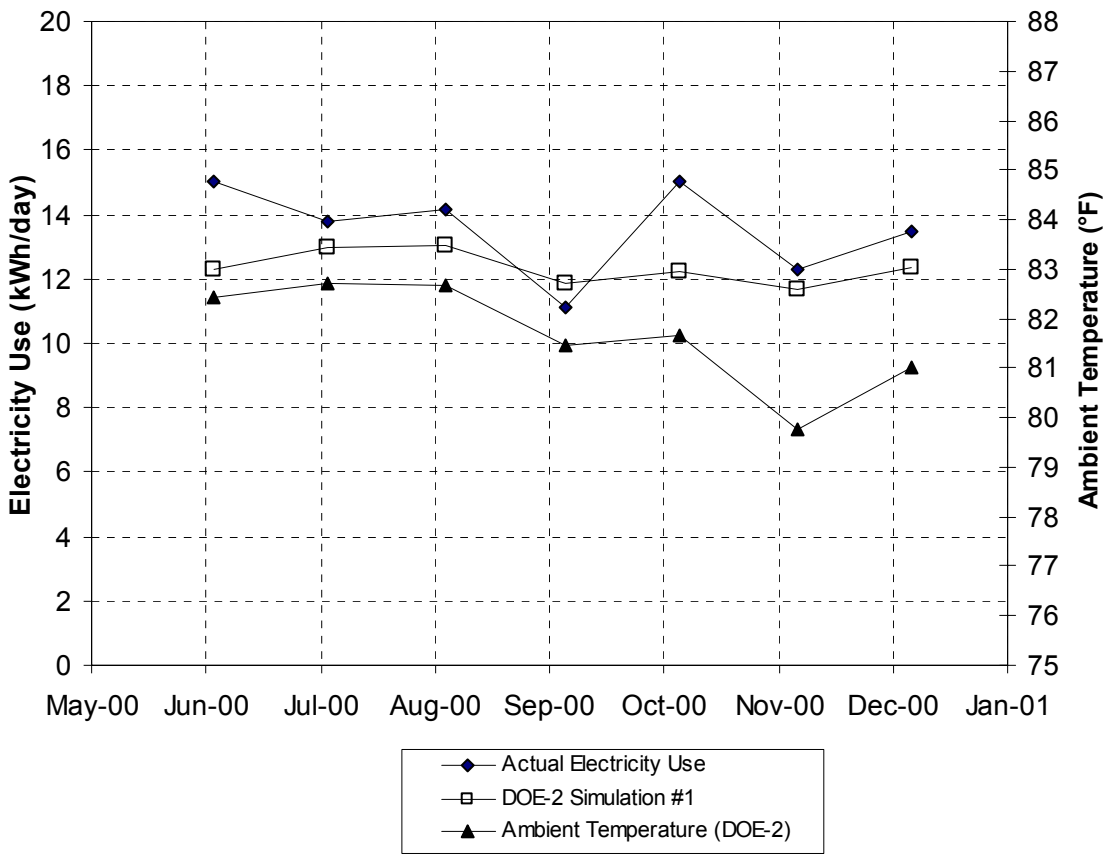


Figure 7.2 *Comparison Between the Actual and Run# 1 Simulated Monthly Average Daily Electricity Use from June to December, 2000*

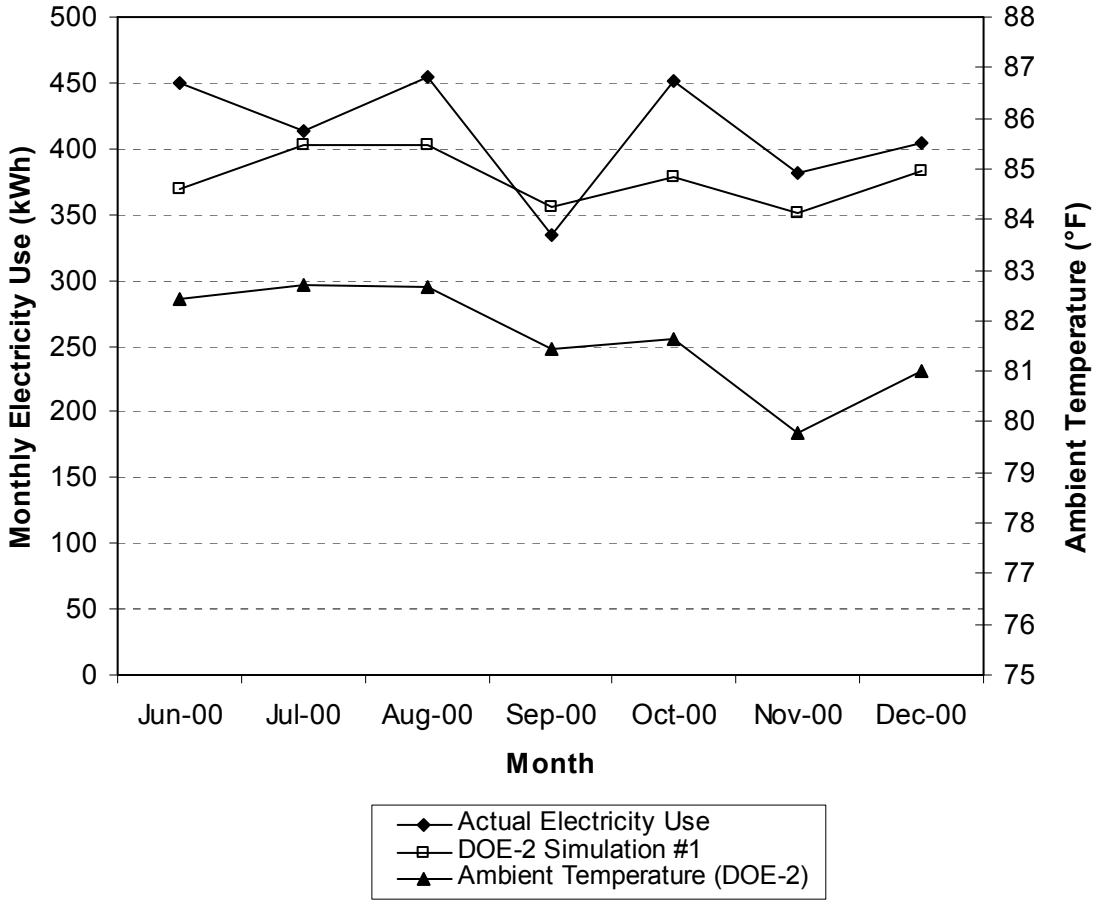
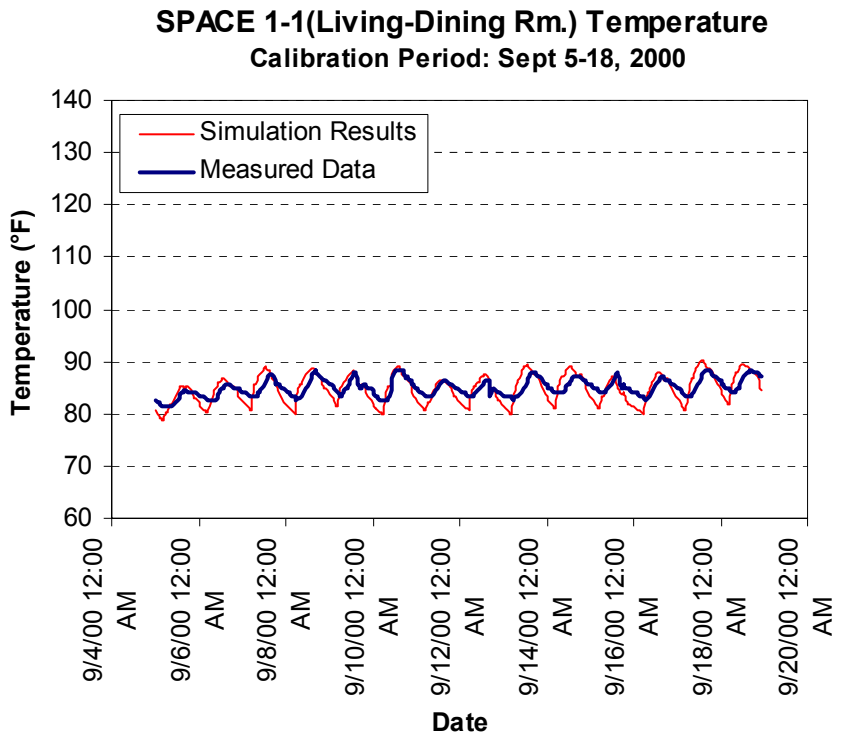


Figure 7.3 *Comparison Between the Actual and Run# 1 Simulated Electricity Use from June to December, 2000*

7.1.2 Zone Temperatures

Figures 7.4 and 7.5 present a 2-week time-series plot of both measured and simulated zone temperatures in four spaces of the case-study house (i.e., the living room, the master bedroom, bedroom-3, and the attic). All results of the measured and the Run# 1 simulated zone temperature comparisons are presented in Appendix D. The RMSE and CV(RMSE) for each zone temperature and the average of all zone temperatures are presented in Table 7.4.



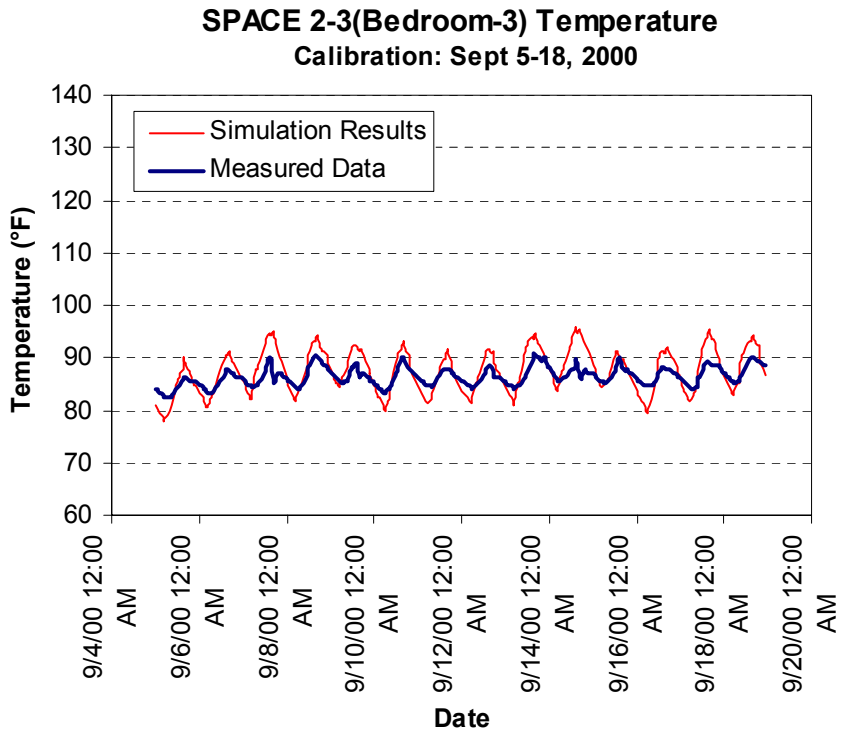


Figure 7.4 *Comparison Between the Measured and the DOE-2 Run# 1 Simulated Temperatures of the Living-Dining Room and Bedroom-3.*

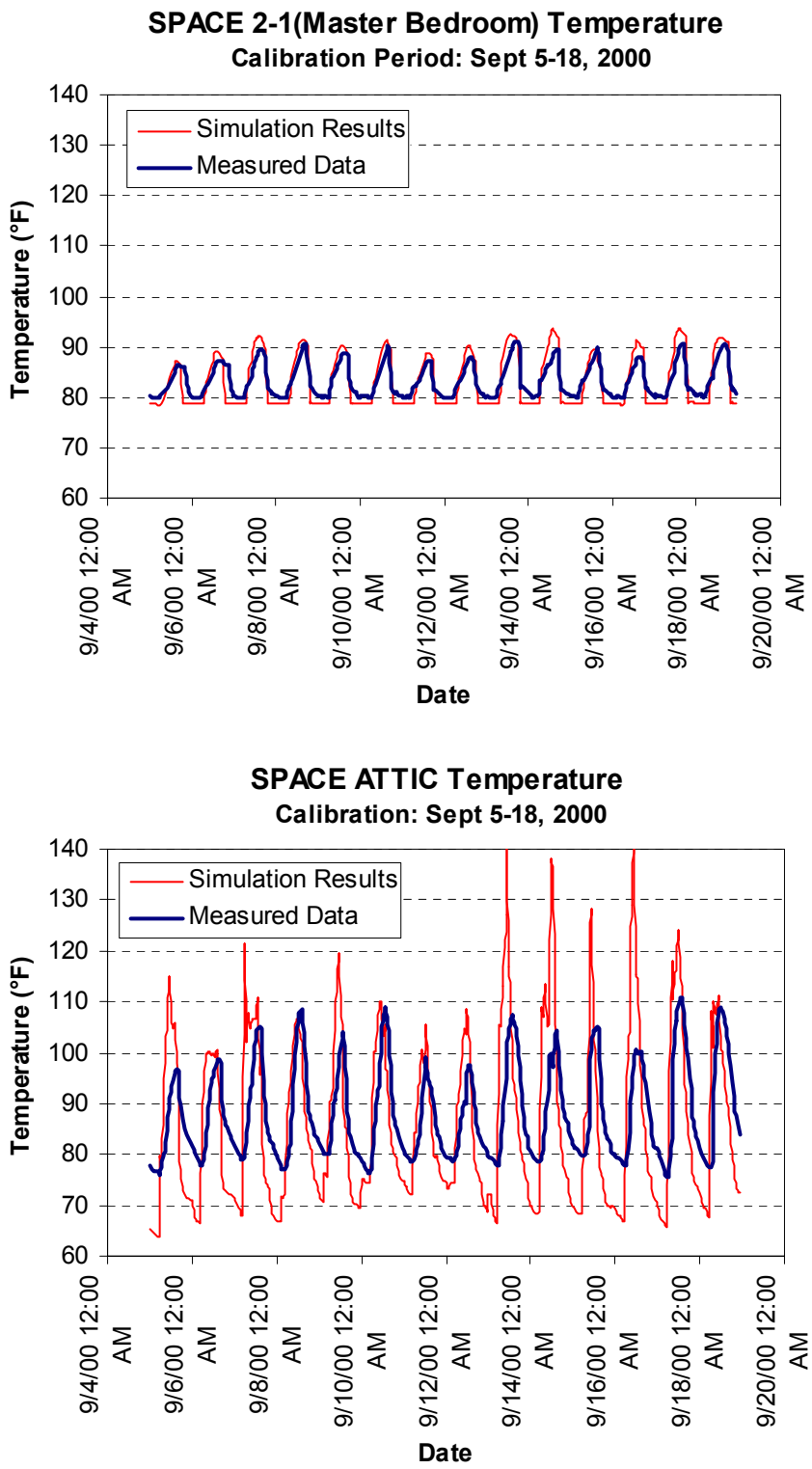


Figure 7.5 *Comparison Between the Measured and the DOE-2 Run# 1 Simulated Temperatures of the Master Bedroom and the Attic.*

From Figures 7.4, 7.5 and Table 7.4, in general the model predicted the simulated zone temperatures of the living spaces (i.e. the living room, the master bedroom, and the attic) fairly well as compared to the simulated attic temperatures. However, in Figure 7.5, the simulated zone temperature of the attic is very different from the measured temperatures in the attic, especially the temperature swings from nighttime to daytime. The simulated attic temperature predicted a wider range as compared to the measured temperatures. The highest temperatures (which occurred in the daytime) reached approximately 140 ºF for the simulated temperature, while only 110 ºF for the measured temperature. The lowest temperatures occurred in the nighttime, reaching approximately 65 ºF for the simulated temperature, and approximately 75 ºF for the measured temperature.

In summary, there were significant differences between the measured and the simulated zone temperatures from the DOE-2 Run# 1, particularly in the attic temperatures. Although the attic is not a living space, its thermal condition affects the adjacent living spaces' thermal conditions through the transfer of heat through the ceiling. The master bedroom, which is an air-conditioned space, is located below the attic, so the attic's thermal condition affects the air conditioning load and therefore the overall energy consumption. Therefore, calibrations for predicted versus measured zone temperatures in all zones including the attic were performed. The process and results of these zone temperature calibrations are presented in the next section.

7.2 Calibrations of the DOE-2 Run# 1

Calibrations of the model's zone temperatures and the building's energy consumption were both performed. In the calibration process, there were also some modeling assumptions in the input file that needed to be modified or added to the file. Corrections made to the first DOE-2 run, as well as the energy use and zone temperature calibrations are all discussed in Section 7.2.1.

7.2.1 Calibration Process

Calibrations of the model's zone temperatures and energy consumption were performed by adjusting the input parameters in the DOE-2 input file, rerunning the simulation, extracting the required data from the new output file and comparing it to the measured data. The calibrations were performed over numerous runs. Table 7.4 shows the adjustments and the

results for each run, which included the RMSE and the CV(RMSE) of the zone temperatures, as well as the whole-building energy consumption. As mentioned earlier, besides the zone temperatures and the building's energy consumption calibrations, corrections were made to the modeling assumptions. These corrections are also described in Table 7.4.

In Table 7.4, the major zone temperature calibration adjustments can be summarized by space, as listed below:

1) SPACE 1-1 (Living-Dining Room)

   - Used effective value of floor area (60% larger than the value in Run# 1)

2) SPACE 2-1 (Master Bedroom)

   - Adjusted windows' transmittance to 50% to account for curtain usage (reduced from 79% in Run# 1)

3) SPACE 2-3 (Bedroom-3)

   - Reduced air change rate from 1.0 in Run# 1 to 0.5

   - Used effective value of volume (200 % larger than Run# 1) and area (100% larger than Run# 1)

4) SPACE-ATTIC (Attic)

   - Created thermal mass walls in the attic and adjusted infiltration schedule (explained in the following paragraph)

In Run #8, high thermal mass walls (i.e., brick walls) were created inside the attic to account for the roof's actual concrete structure and the brick walls that are present in the case-study house's attic (see Figure 5.2). This caused the CV(RMSE) to drop from 19.33 percent to 7.64 percent. Also, additional adjustments were made to the attic in later runs. The effective wall area was later increased from 1,200 ft^2 to 1,600 ft^2 in Run #9. Also, in Run #9, the attic's infiltration schedule was adjusted; the nighttime air-change rate (from 6 p.m. to 6 a.m.) was set to 15 and the daytime air-change rate was set to 1. The adjustment of the wall area and the infiltration schedule reduced the CV(RMSE) from 7.64 to 6.47 percent.

From Table 7.4, the whole-building energy use (WBEU) was directly adjusted by the lighting and equipment schedules (Run #11 and Run #14), and adjustments to the parameters of the building's systems. In Run #14, the energy use by the refrigerators was revised, using detailed information about the refrigerators was obtained from the homeowner. This adjustment to the equipment energy use did, in fact, increase the difference in the WBEU. The WBEU was also indirectly adjusted by the calibration of the zone temperatures. However, this effect did not have a substantial impact on the monthly energy use prediction.

There was also an important correction made to the model's building system. In the early runs, an instantaneous compact water heater was specified in the model as equipment that was present in the second floor bathroom. The load was estimated from the rated power of that water heater. A water heater should be specified as part of a building's system, since its energy consumption depends on usage schedule and the environment (i.e., ground temperature). Thus, the instantaneous compact water heater was later assigned as a domestic hot water system in the PLANT section of Run #10, instead of an equipment load in SPACE 2-4. After assigning the water heater in Run #10, adjustments were made to the water flow rate to match the simulated energy use of the water heater to the estimated energy use calculated from the actual data provided by the occupants. (i.e., the schedule of usage).

TABLE 7.4

Model Building's Energy Use and the Zone Temperature Calibration Process

Run	Changes Made to Model	Space	RMSE (° F) and CV(RMSE) (%) of WBEU	RMSE (° F) and CV(RMSE) (%) of Zone Temperature
1	Base Model Basic Input Parameters: 1) Air Change/hr = 1 (Attic = 30) 2) Floor Weight = 0 (Used custom weighting factors) 3) Thermostat Set Point of Conditioned Space = 78.8 ° F (Set-point temperature data were obtained from the occupants)	Space 1-1: Living Rm.		1.97 ° F 2.31 %
		Space 2-1: Master Bedroom		2.53 ° F 3.03 %
		Space 2-3: Bedroom-3		2.79 ° F 3.23 %
		Sapce Attic: Attic		13.24 ° F 15.04 %
		Average RMSE Average CV(RMSE)	**1.67** kWh/day **12.33** %	**3.48** ° F **3.96** %
2	1) Applied U-EFFECTIVE command for the ground floors 2) Changed DOE-2 material library code from CC14 to CC03 (Undried heavy weight to dried heavy weight)	Space 1-1: Living Rm.		10.55 ° F 12.42 %
		Space 2-1: Master Bedroom		2.34 ° F 2.81 %
		Space 2-3: Bedroom-3		2.63 ° F 3.04 %
		Sapce Attic: Attic		13.23 ° F 15.03 %
		Average RMSE Average CV(RMSE)	**3.37** kWh/day **24.84** %	**4.32** ° F **4.98** %
3	1) Corrected MAT-FIC-1 value MAT-FIC-1 = MATERIAL RESISTANCE = 2.437 2) Corrected Floor Weight of ceiling to = 0	Space 1-1: Living Rm.		15.39 ° F 18.11 %
		Space 2-1: Master Bedroom		2.24 ° F 2.69 %
		Space 2-3: Bedroom-3		2.44 ° F 2.82 %
		Sapce Attic: Attic		13.23 ° F 15.03 %
		Average RMSE Average CV(RMSE)	**2.19** kWh/day **16.12** %	**5.14** ° F **5.96** %
4	1) Space 1-1: Used nominal volume (60%) 2) Space 2-1: Increased opaqueness of the glass to account for curtains (transmittance = 50%) Thermostat Set Point = 79.8 ° F 3) Space 2-3: Reduced Air-Change to 0.5 and used nominal value of floor area (30% larger than the actual) 4) Space-Attic: Adjusted Air-Change to 60	Space 1-1: Living Rm.		3.56 ° F 4.19 %
		Space 2-1: Master Bedroom		2.22 ° F 2.67 %
		Space 2-3: Bedroom-3		2.73 ° F 3.16 %
		Sapce Attic: Attic		12.73 ° F 14.47 %
		Average RMSE Average CV(RMSE)	**1.89** kWh/day **13.94** %	**3.42** ° F **3.90** %
5	1) Adjusted window transmittance of Space 1-1, 1-2 and 2-3 to 50% 2) Created shading for Space 2-3 (Space 1-2's north wall is as a vertical fin to Space 2-3) 3) Space Attic: changed absorbtance value of the roof tile absorbrance = 0.88 (dark brown paint) 4) Added SHADING-SURFACE = YES for the roof	Space 1-1: Living Rm.		3.03 ° F 3.57 %
		Space 2-1: Master Bedroom		2.30 ° F 2.76 %
		Space 2-3: Bedroom-3		2.66 ° F 3.08 %
		Sapce Attic: Attic		14.94 ° F 16.97 %
		Average RMSE Average CV(RMSE)	**1.88** kWh/day **13.88** %	**3.91** ° F **4.46** %
6	1) SPACE 1-3: Assigned as PLENUM (changed from unconditioned space) 2) SPACE 2-3: Used nominal value of volume and area of the space (200% and 100% respectively) and added an interior wall next to in SPACE1-2	Space 1-1: Living Rm.		3.05 ° F 3.59 %
		Space 2-1: Master Bedroom		2.27 ° F 2.73 %
		Space 2-3: Bedroom-3		1.59 ° F 1.83 %
		Sapce Attic: Attic		14.94 ° F 16.98 %
		Average RMSE Average CV(RMSE)	**1.87** kWh/day **13.77** %	**3.87** ° F **4.41** %

TABLE 7.4
(Continued)

Run	Changes Made to Model	Space	RMSE (° F) and CV(RMSE) (%) of WBEU	RMSE (° F) and CV(RMSE) (%) of Zone Temperature
7	1) SPACE-ATTIC: Created interior wall that should have been present, and changed Air-Change to 1 for day-time and 5 for nighttime (i.e., edited infiltration schedule)	Space 1-1: Living Rm.		3.08 ° F 3.62 %
		Space 2-1: Master Bedroom		2.49 ° F 2.98 %
		Space 2-3: Bedroom-3		1.79 ° F 2.07 %
		Sapce Attic: Attic		17.01 ° F 19.33 %
		Average RMSE Average CV(RMSE)	**1.78** kWh/day **13.12** %	**4.39** ° F **5.00** %
8	1) Created SPACE-ATTIC-2 that is in SPACE-ATTIC SPACE-ATTIC-2 has only interior walls (1200 ft2) (Put a massive wall inside the attic to represent the roof's concrete structure and walls in the attic)	Space 1-1: Living Rm.		3.07 ° F 3.61 %
		Space 2-1: Master Bedroom		2.19 ° F 2.63 %
		Space 2-3: Bedroom-3		1.60 ° F 1.85 %
		Sapce Attic: Attic		6.75 ° F 7.67 %
		Average RMSE Average CV(RMSE)	**1.63** kWh/day **12.02** %	**1.97** ° F **2.27** %
9	1) SPACE-ATTIC-2: Increased interior wall area to 1600 sq.ft., volume = 1000 cu.ft and use infiltration schedule of SPACE-ATTIC SPACE-ATTIC: Adjusted infiltration schedule 1 for daytime, 15 for nighttime (starting at 6 PM) 2) SPACE-LIVING: Adjusted monthly ground temperatures (from Sreshthaputra, 2003) to 2 °F lower. and used nominal values of the floor area (50% larger)	Space 1-1: Living Rm.		2.68 ° F 3.15 %
		Space 2-1: Master Bedroom		2.10 ° F 2.52 %
		Space 2-3: Bedroom-3		1.49 ° F 1.72 %
		Sapce Attic: Attic		5.69 ° F 6.47 %
		Average RMSE Average CV(RMSE)	**1.65** kWh/day **12.13** %	**1.70** ° F **1.95** %
10	1) Corrected hot water heater specified in equipment by specicifying in PLANT ASSIGNMENT instead	Space 1-1: Living Rm.		2.59 ° F 3.05 %
		Space 2-1: Master Bedroom		2.08 ° F 2.50 %
		Space 2-3: Bedroom-3		1.53 ° F 1.77 %
		Sapce Attic: Attic		6.73 ° F 7.65 %
		Average RMSE Average CV(RMSE)	**1.19** kWh/day **8.62** %	**1.92** ° F **2.20** %
11	1) Reduced Energy use by Equipment 2) Lowered ground temperature 1.5 F 3) Lowered Flow Rate of DHW	Space 1-1: Living Rm.		2.34 ° F 2.76 %
		Space 2-1: Master Bedroom		2.07 ° F 2.49 %
		Space 2-3: Bedroom-3		1.50 ° F 1.74 %
		Sapce Attic: Attic		6.73 ° F 7.65 %
		Average RMSE Average CV(RMSE)	**0.97** kWh/day **7.00** %	**1.89** ° F **2.17** %
12	1) Space 1-1 Increased Floor Area (Used nominal value) 60% larger than the actual one 2) Put surrounding buildings in the east and south 3) Applied SHADING-SCHEDULE of window F-1-1 SPACE1-1 (accounted for curtain usage)	Space 1-1: Living Rm.		0.94 ° F 1.11 %
		Space 2-1: Master Bedroom		1.59 ° F 1.91 %
		Space 2-3: Bedroom-3		1.34 ° F 1.55 %
		Sapce Attic: Attic		6.37 ° F 7.24 %
		Average RMSE Average CV(RMSE)	**1.02** kWh/day **7.39** %	**1.69** ° F **1.93** %

TABLE 7.4

(Continued)

Run	Changes Made to Model	Space	RMSE (° F) and CV(RMSE) (%) of WBEU	RMSE (° F) and CV(RMSE) (%) of Zone Temperature
13	1) Used monthly ambient temperatures from the weather file as monthly ground termperature (Kusuda, 1965) 2) Adjusted water flow rate to 2.25 GPM 3) Added window frames that were missing in the model	Space 1-1: Living Rm.		1.10 ° F 1.29 %
		Space 2-1: Master Bedroom		1.62 ° F 1.95 %
		Space 2-3: Bedroom-3		1.38 ° F 1.59 %
		Sapce Attic: Attic		6.38 ° F 7.25 %
		Average RMSE Average CV(RMSE)	**0.96** kWh/day **6.95** %	**1.70** ° F **1.94** %
14	1) Adjusted Lighting and Equipment Schedules	Space 1-1: Living Rm.		1.27 ° F 1.49 %
		Space 2-1: Master Bedroom		1.61 ° F 1.93 %
		Space 2-3: Bedroom-3		1.38 ° F 1.59 %
		Sapce Attic: Attic		6.38 ° F 7.25 %
		Average RMSE Average CV(RMSE)	**2.19** kWh/day **15.87** %	**1.71** ° F **1.95** %
15	1) Adjusted amount of DHW use to match the estimated energy use by the hot water heater	Space 1-1: Living Rm.		1.27 ° F 1.49 %
		Space 2-1: Master Bedroom		1.61 ° F 1.93 %
		Space 2-3: Bedroom-3		1.38 ° F 1.59 %
		Sapce Attic: Attic		6.38 ° F 7.25 %
		Average RMSE Average CV(RMSE)	**1.33** kWh/day **9.63** %	**1.71** ° F **1.95** %
16	1) Adjusted Lighting and Equipment Schedules and energy use by the refrigerators 2) Used window library glass (code number > 1000) and added window frames	Space 1-1: Living Rm.		1.14 ° F 1.34 %
		Space 2-1: Master Bedroom		1.52 ° F 1.82 %
		Space 2-3: Bedroom-3		1.17 ° F 1.36 %
		Sapce Attic: Attic		6.36 ° F 7.22 %
		Average RMSE Average CV(RMSE)	**0.94** kWh/day **6.81** %	**1.68** ° F **1.92** %

7.2.2 Calibrated Monthly Energy Use

Figure 7.6 presents the results of the calibrated monthly average daily energy use, which were the results of RUN # 16. The figure shows that there were some differences between the actual and the calibrated data; the calibrated model under predicted the energy use in June, September, and October, and over predicted the energy use in July, August, November, and December. However, as can be seen in the graph, the profile of the simulated energy use is similar to that of the actual energy use. There was relatively high energy consumption in July, August, and October, while September there was the lowest month. The occupants of the house

reported that they had a vacation (4 days) in September, which helps to explain the low energy use in this month.

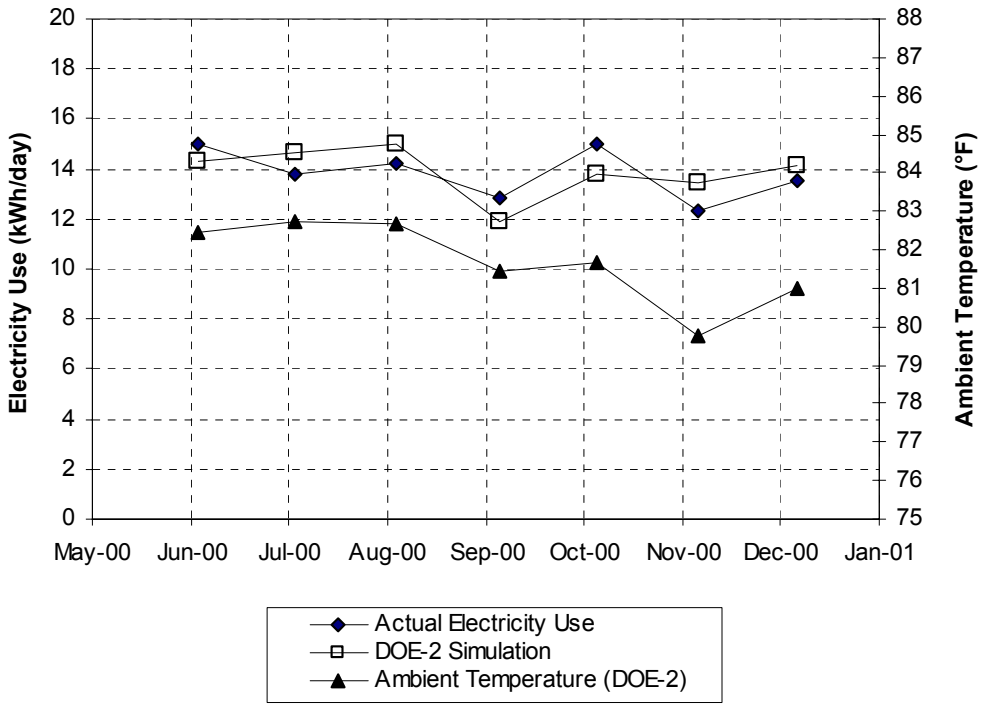


Figure 7.6 *Comparison Between the Actual Utility Bills and the Run# 16 Simulated Monthly Average Daily Electricity Use from June to December, 2000.*

Figure 7.7 shows the total monthly electricity use, and domestic hot water (DHW) electricity use, which repeats the results of RUN # 16. The results of the simulated monthly energy use as compared to the actual energy use were similar to the results of monthly average daily energy use that are presented in Figure 7.6. The simulated results from RUN #16 were considered sufficiently close to the actual data to declare RUN #16 as the calibrated base-case model. Table 7.5 and Figures 7.8 present the results of an annual simulation from RUN #16.

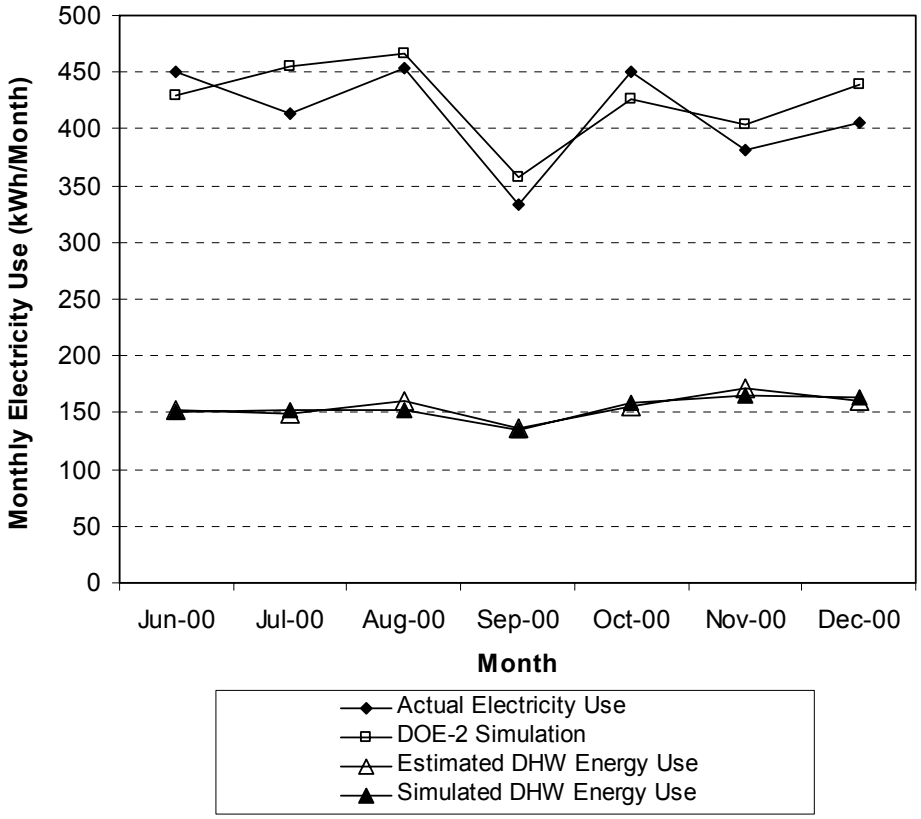
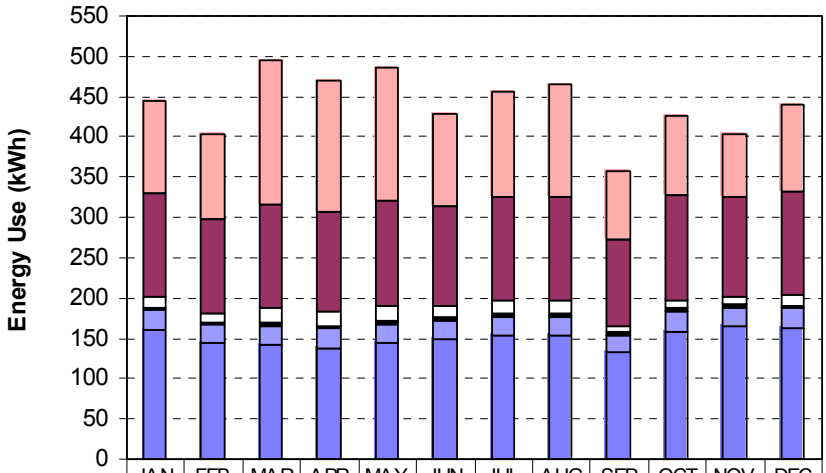


Figure 7.7 *Comparison Between the Actual and Run #16 Simulated Electricity Use, including the Domestic Hot Water Energy Use from June to December, 2000.*

TABLE 7.5

Calibrated Model (Base Case) Monthly Electricity Use

Month	Lighting (kWh)	Equipment (kWh)	Cooling (kWh)	Pump (kWh)	Vent Fans (kWh)	DHW (kWh)	Energy use (kWh/month)	Period (days)	Avg. Energy use (kWh/day)
January	24	129	118	4	13	161	449	31	14.48
February	22	116	111	3	12	145	409	28	14.61
March	24	128	185	4	20	142	503	31	16.23
April	24	125	168	4	18	138	477	30	15.90
May	24	129	175	4	20	144	496	31	16.00
June	23	124	122	4	14	150	437	30	14.57
July	24	129	140	4	16	153	466	31	15.03
August	24	128	149	4	17	153	475	31	15.32
September	20	107	89	3	10	134	363	30	12.10
October	24	129	105	4	12	159	433	31	13.97
November	23	124	83	4	9	165	408	30	13.60
December	24	129	112	4	13	163	445	31	14.35
Jan to Dec.	280	1497	1557	46	174	1807	5361	214	14.68



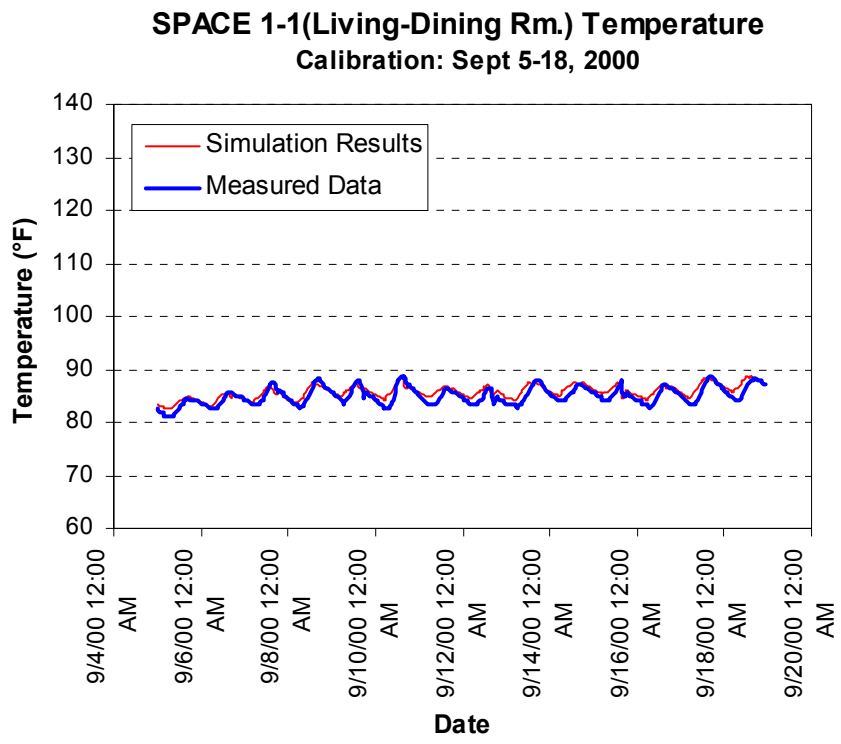
	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
Cooling (kWh)	113	106	178	161	166	115	130	141	84	100	79	107
Equipment (kWh)	129	116	128	125	129	124	129	128	107	129	124	129
Vent Fans (kWh)	13	12	19	17	19	13	15	16	9	11	9	12
Pump (kWh)	4	3	4	4	4	4	4	4	3	4	4	4
Lighting (kWh)	24	22	24	24	24	23	24	24	20	24	23	24
DHW (kWh)	161	145	142	138	144	150	153	153	134	159	165	163

Figure 7.8 *Base Case Monthly Energy Use: January to December, 2000.*

7.2.3 Calibrated Zone Temperatures

Figures 7.9 and 7.10 present 2-week time-series plots of both measured and simulated zone temperatures in four spaces of the case-study house (i.e., the living room, the master bedroom, bedroom-3, and the attic). All results of the measured data and the Run# 16 simulated zone temperature comparisons are presented in Appendix D. The RMSE and CV(RMSE) for each zone temperature and the average of all zone temperatures are presented in Table 7.4.

From Figures 7.9 and 7.10, it can be seen that the simulated zone temperatures in all spaces were significantly closer to the actual data than the results of Run# 1 (see Figures 7.4. and 7.5). This is especially so for the simulated attic temperatures, which were substantially improved.



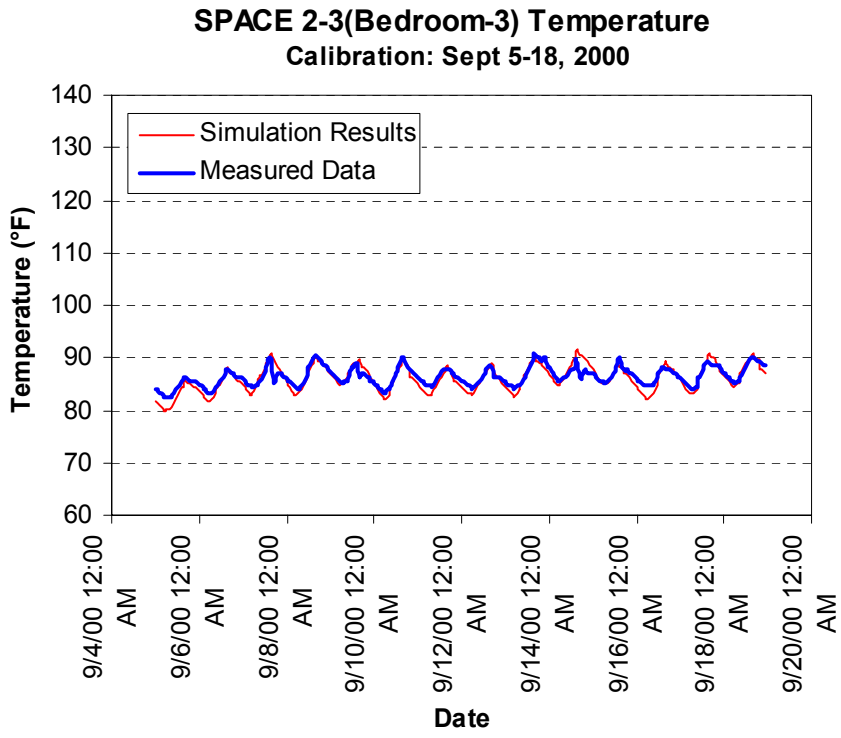


Figure 7.9 *Comparison Between the Measured Data and Run #16 Simulated Temperatures of the Living-Dining Room and Bedroom-3.*

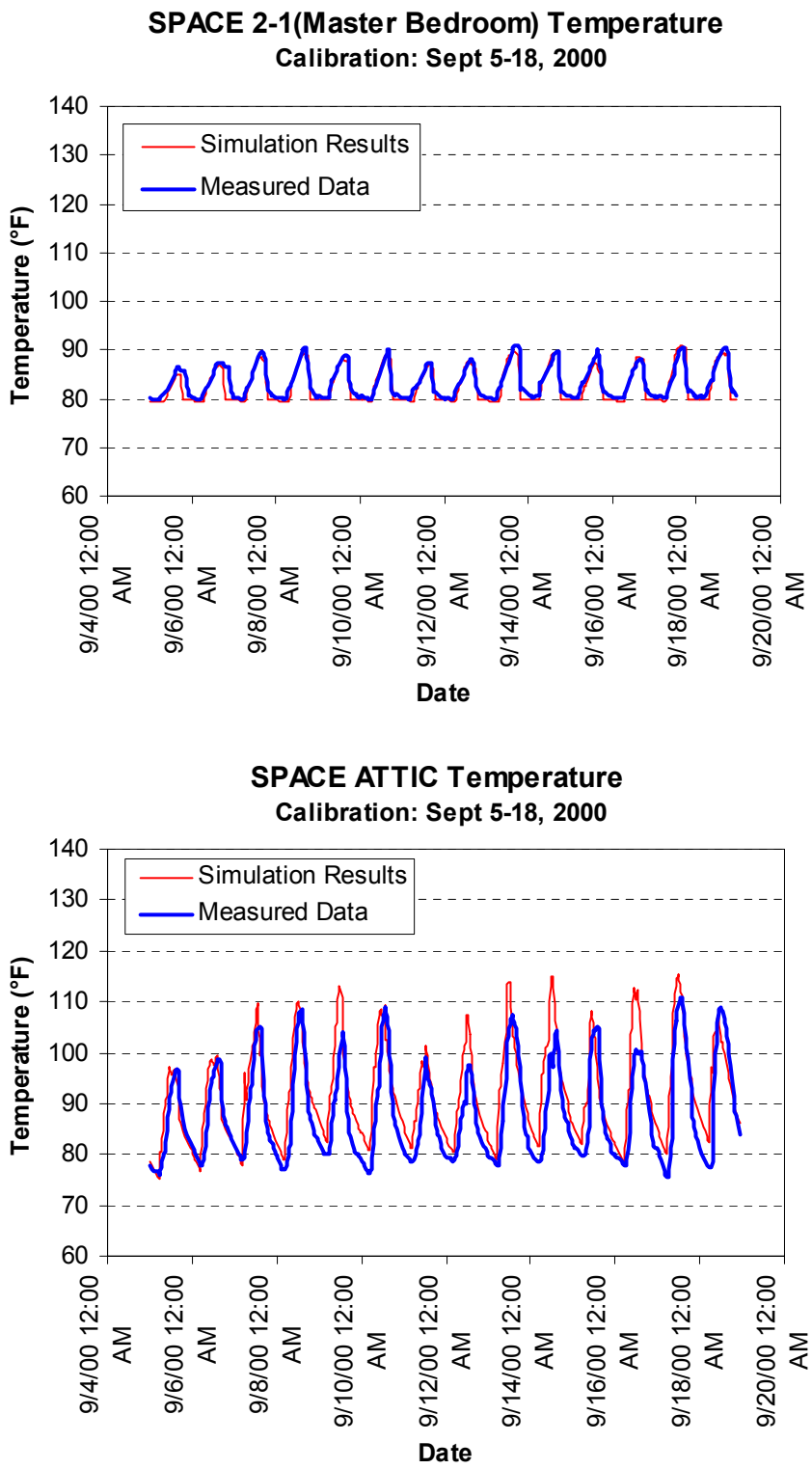


Figure 7.10 *Comparison Between the Measured Data and Run #16 Simulated Temperatures of the Master Bedroom and the Attic.*

7.3 Investigation of Energy Efficient Strategies and Results

Once the model was calibrated to the case-study house, nine energy efficiency strategies and two renewable energy systems (i.e., the hybrid PV-T^2 collector system and the photovoltaic system) were then analyzed to determine which were the most efficient. The individual energy efficiency strategies were also combined with other energy efficiency strategies and renewable energy technologies. Descriptions of these energy efficiency strategies and renewable energy systems, as well as their combinations are shown in Table 7.6. Additional information about each measure including the inputs to the DOE-2, F-CHART or PV F-CHART programs can be found in Appendices D and F.

TABLE 7.6

Summary of Building Improvement Strategies

Building Improvement Strategy No.	Concept	Strategy	Description
1	Lower or eliminate heat coming through the roof	Improve the roof's insulation	Increase heat resistance of insulation placed behind the roof's tiles (i.e., not on the 2nd floor ceiling) 1) Strategy 1-1: R-7 fiberglass insulation 2) Strategy 1-2: R-14 fiberglass insulation
2	Lower or eliminate heat coming through the roof	Improve the ceiling's insulation in the attic	Increase heat resistance of insulation placed on the 2nd floor ceiling (upgraded from existing R-11 to R-28 fiberglass insulation)
3	Lower or eliminate heat coming through the walls	Improve the wall's heat resistance	Use high R-value light-weight concrete block 1) Strategy 3-1: 4"(10 cm) light-weight concrete block 2) Strategy 3-2: 6"(15 cm) light-weight concrete block 3) Strategy 3-3: 4" light-weight concrete block with insulation on the outside wall 4) Strategy 3-4: 4" light-weight concrete block with insulation on the inside wall

TABLE 7.6

(Continued)

4	Lower or eliminate heat coming through the windows	Use Low-e windows	Replace single-pane clear glass with double-pane low-e glazing (tinted)
5	Lower or eliminate heat coming through the windows	Use shading devices for the windows	Install vertical and horizontal fins for windows on south, east and west
6	Balance/lower interior temperatures using high thermal mass exterior walls	High thermal mass wall	Increase mass of existing wall (4" brick): 1) Strategy 6-1: 8"(20 cm) brick wall 2) Strategy 6-2: 12"(30 cm) brick wall
7	Improve efficiency of the air conditioning system	Use highly energy efficient air conditioning systems	Use SEER-12 air conditioning systems
8	Improve efficiency of the lighting system	Use electronic ballasts	Replace magnetic ballasts of 32 W T-9 Circline lamps with electronic ballasts
9	Improve efficiency of the refrigerators	Replace existing refrigerators with highly energy efficient refrigerators	Use the highest standard refrigerators (with the same volume of existing ones)
10 [Renewable Energy Technology (RET) 1]	Generate on-site thermal (DHW) and electrical energy	Install a hybrid PV-T^2 collector system	A hybrid PV-T^2 collector system was installed to supply all DHW needs. The electricity output from the system is a supplemental energy for the base case.
11 [Renewable Energy Technology (RET) 2]	Generate on-site electric energy	Install a photovoltaic system	A photovoltaic system was installed to supply electricity to the base case.
12 [Renewable Energy Technology (RET) 3]	Generate on-site thermal (DHW) and electrical energy	Install a hybrid PV-T^2 collector system and a photovoltaic system	To increase the renewable electricity supply by the RET-1 to the base case, a photovoltaic system (RET-2) was included in the system.

TABLE 7.6

(Continued)

13 [Renewable Energy Technology (RET) 4]	Generate on-site thermal (DHW) by flat plate solar collector	Install a flat plate solar collector system (a typical type of solar collectors)	To increase the thermal efficiency of the solar DHW system (The hybrid PV-T^2 collector was not included in this strategy)
Combination A	Combination of strategies that improve building's envelope, building systems, and a major appliance.	Combine strategies 2,3-4, 7,8, and 9	-Increase 2nd floor ceiling's insulation (R-28) -Light-weight concrete walls with insulation on the inside wall -Energy efficient air conditioners -Electronic ballasts -Energy efficient refrigerators
Combination B	Combination of strategies that improve the building's envelope (including low-e windows), building systems, and a major appliance	Combination A + Strategy 4 (low-e windows)	-Increase 2nd floor ceiling's insulation (R-28) -Light-weight concrete walls with insulation on the inside wall -Energy efficient air conditioners -Electronic ballasts -Energy efficient refrigerators -Low-e windows
Combination C	Combination of strategies that improve the building's envelope, building systems, a major appliance, and shading devices	Combination A + Strategy 5 (shading devices)	-Increase 2nd floor ceiling's insulation (R-28) -Light-weight concrete walls with insulation on the inside wall -Energy efficient air conditioners -Electronic ballasts -Energy efficient refrigerators -Shading devices
Combination D	Combination of strategies that improve the building's envelope (including low-e windows), building systems, a major appliance, and shading devices	Combination A + Strategies 4 and 5	-Increase 2nd floor ceiling's insulation (R-28) -Light-weight concrete walls with insulation on the inside wall -Energy efficient air conditioners -Electronic ballasts -Energy efficient refrigerators -Low-e windows -Shading devices
Combination E	Combination of energy efficiency measures and a renewable energy system.	Combination D with PV-T^2 collector system	Energy reduction from all strategies (except 1,2, and 6) and supplemental energy from the PV-T^2 collector system

TABLE 7.6

(Continued)

Combination F	Combination of energy efficiency measures and a renewable energy system	Combination D with photovoltaic system	Energy reduction from all strategies (except 1,2, and 6) and supplemental energy from the photovoltaic system
Combination G	Combination of energy efficiency measures and renewable energy systems	Combination D with PV-T^2 collector system and photovoltaic system	Energy reduction from all strategies (except 1,2, and 6) and supplemental energy from the PV-T^2 collector system and the photovoltaic system

The hourly data for one-day (September 17, 2000) that included simulated zone temperatures from the DOE-2 simulation are used to present the impact of the building's improvement strategies on the space temperatures. September 17, 2000, was chosen because it was a clear day. The solar load, which is high on clear days, was a target for reduction by energy efficiency strategies, as presented in Table 7.6. Weather conditions for September 17, 2000, which include the dry-bulb temperature, relative humidity, wind speed, and solar radiation, are all shown in Figure 7.11.

The DOE-2 input data and the output (the building energy performance summary or BEPS report) of those individual energy efficiency strategies that changed the base-case model are presented in Appendix D. The BEPS report for combinations A through G are also presented in Appendix D. The F-Chart and PV-F Chart's input data and results are all presented in Appendix F.

The following sections present the results from the building's improvement strategies shown in Table 7.6. Sections 7.3.1 to 7.3.9 present the results from the analysis of individual energy efficiency strategies. Sections 7.3.10 to 7.3.12 present the results from the analysis of renewable energy systems (i.e., the hybrid PV-T^2 collector system and the photovoltaic system). Sections 7.3.13 to 7.3.19 present the results of the analysis of these combinations of the energy efficiency strategies and renewable energy systems.

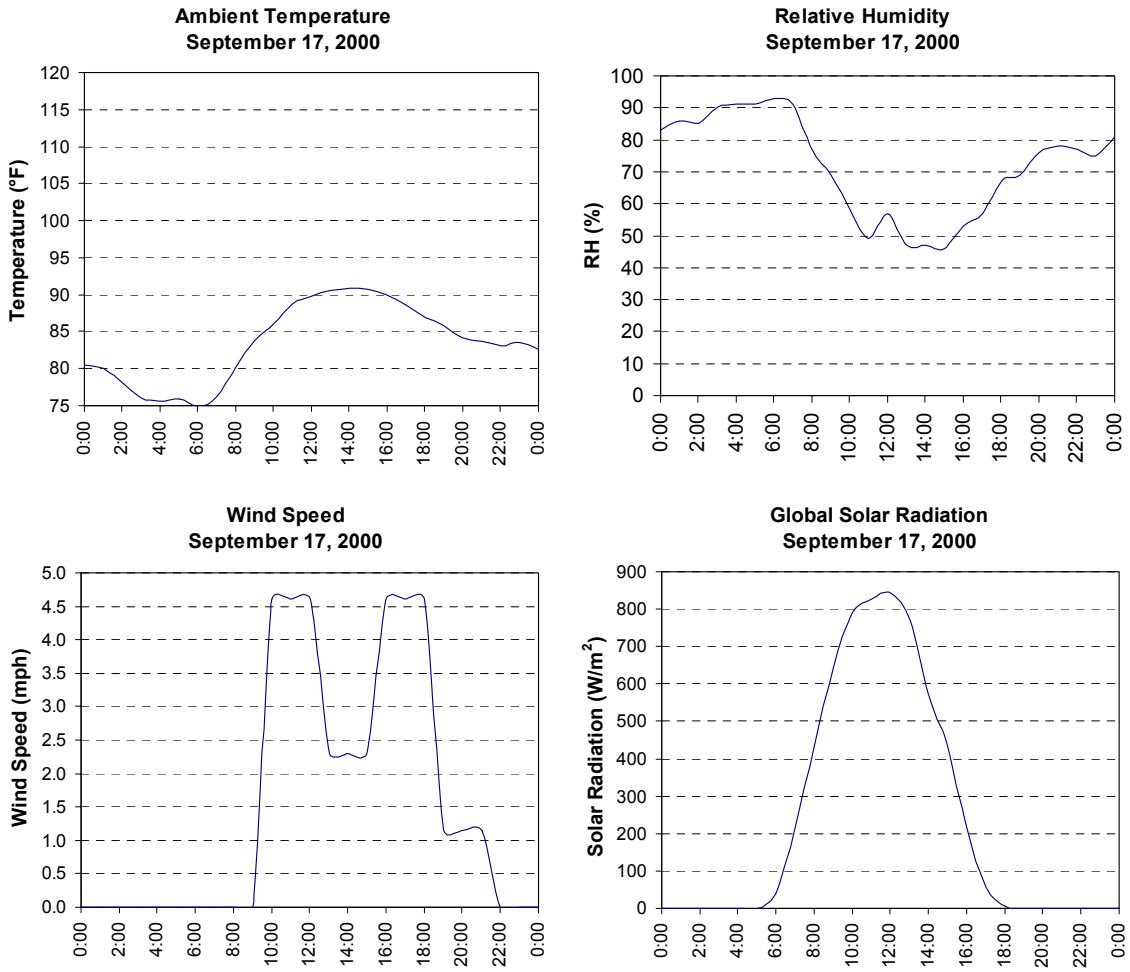


Figure 7.11 *Weather Conditions in Bangkok on September 17, 2000 (from DOE-2 Output).*

7.3.1 Strategy 1: Improve the Roof's Insulation

Strategy 1 was one of the energy efficiency strategies that aimed to improve the case-study building's envelope. The case-study house had no insulation installed behind its concrete roof tiles. Concrete roof tile is a high thermal mass building material that can store and transfer the solar load to the attic, and then to the living spaces that are below that attic. Thus, placing insulation behind the roof tile was analyzed to see how well it blocked or minimized the solar load from the attic to the living spaces. It was anticipated that this should help lower the second

floor's air temperatures which were normally high, especially during the daytime. This strategy would also help reduce air conditioning energy use in those spaces under the attic. R-7 and R-14 fiberglass insulations were inserted into the DOE-2 model as indicated in Appendix D. The results of the R-7 and R-14 insulation addition are shown in Sections 7.3.1.1 and 7.3.1.2

7.3.1.1 Strategy 1-1: R-7 Fiberglass Insulation Underside the Roof Tiles

Figure 7.12 shows the simulated annual energy use of the improved roof insulation (Strategy 1-1), as compared to the base-case house. The Building Energy Performance Summary (BEPS) of the improved Strategy 1-1 as compared to the base case is also shown in Table 7.7. From Figure 7.12 and Table 7.7, it can be seen that energy used for space cooling and ventilation fans was reduced by 1.8 and 1.2 percent respectively. This resulted in a decrease of total energy consumption by 0.5 percent, or 28 kWh per year, which had modest decrease on the cooling energy use and even less decrease on the annual energy use.

TABLE 7.7

Building Energy Performance Summary: Base Case vs. Strategy 1-1

Category of Use	Annual Site Energy Consumptions			
	Base case	Improved Model	Energy Saved	
	kWh	kWh	kWh	(%)
Area Lights	280	280	0	0.0
Equipment	1497	1497	0	0.0
Space Cooling	1480	1454	26	1.8
Pumps	46	46	0	0.0
Vent Fans	165	163	2	1.2
Domestic Hot Water	1807	1807	0	0.0
Total	**5275**	**5247**	**28**	**0.5**

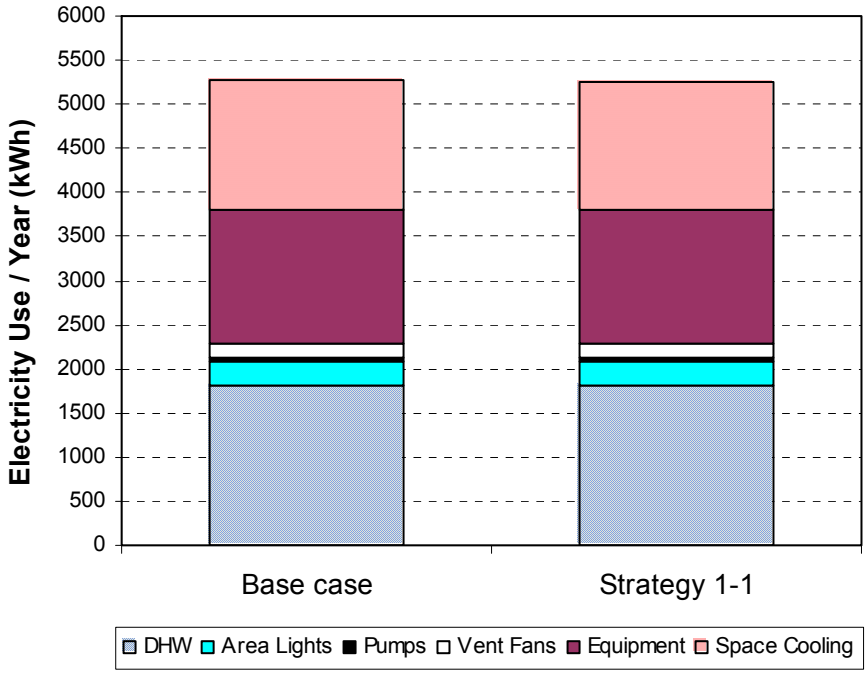


Figure 7.12 *Comparison of Annual Energy Use in the Base Case and Building Improvement Strategy 1-1.*

Figure 7.13 shows the simulated zone temperatures of the improved model as compared to the base case. In the lower right graph in Figure 7.13, it can be seen that, in general, air temperatures in the attic dropped dramatically after the R-7 insulation was installed on the underside of the roof tiles. The peak temperature, which occurred around noon, dropped from 115 ºF to approximately 95 ºF. However, the peak of 95 ºF occurred over a longer period (around 2 hours – from noon to 2:00 p.m.).

The decreased temperatures in the attic resulted in a small decrease of temperatures in the master bedroom and bedroom-3 in both the daytime and the evening, as shown in the lower left and upper right graphs in Figure 7.13, respectively. Bedroom-3 was not conditioned, so the decreased temperatures in this space did not contribute to the energy reduction in the air conditioning system. Instead, the reduction was due to the lower cooling loads on the conditioned spaces (i.e. the master bedroom and bedroom-2). In the first floor space, the living room's temperature did not change, as shown in the upper left graph of Figure 7.13.

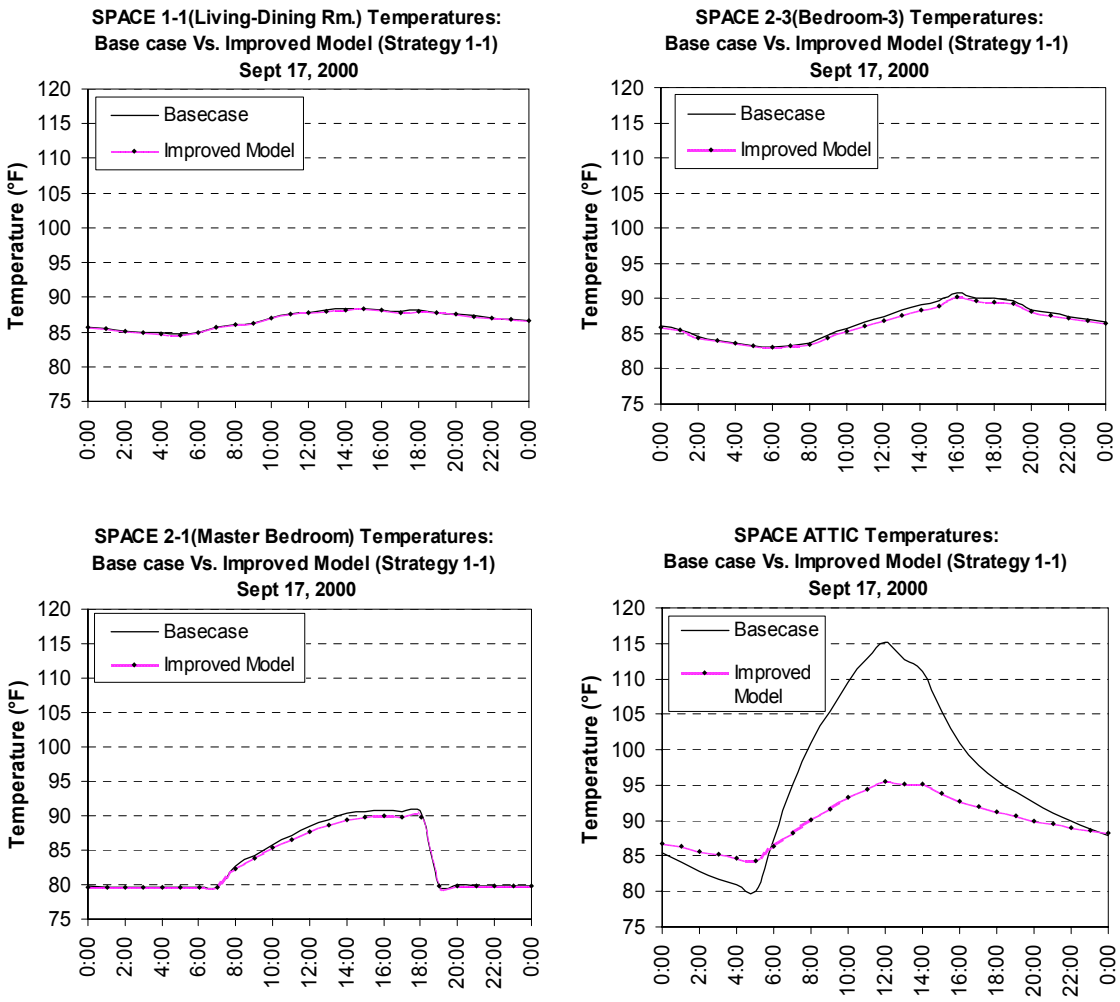


Figure 7.13 *Comparison Between Base Case and Strategy 1-1 Space Temperatures.*

7.3.1.2 Strategy 1-2: R-14 fiberglass Insulation Underside the Roof Tiles

Figure 7.14 shows the annual energy use of the improved model using Strategy 1-2, R-14 fiberglass insulation as compared to the base case. The BEPS output of the improved model Strategy 1-2 as compared to the base case is shown in Table 7.8. From Figure 7.14 and Table 7.8, energy used for space cooling and ventilation fans was reduced by 2.5 and 3 percent respectively. This resulted in a small decrease of total energy consumption by 0.8 percent, or

42 kWh per year, which had a small, but noticeable impact on the cooling energy use, and a very small impact on the annual energy use.

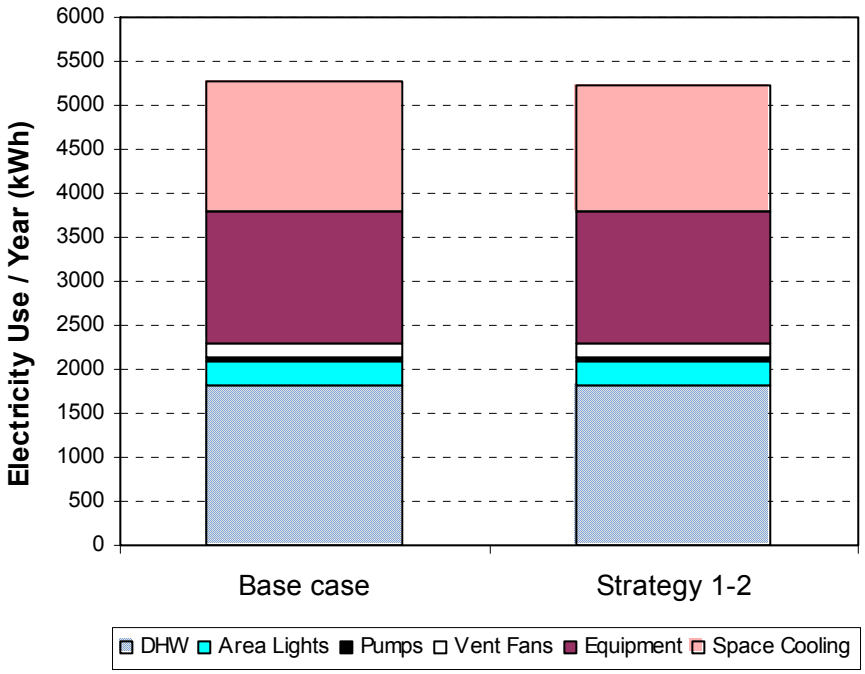


Figure 7.14 *Comparison of the Annual Energy Use of the Base Case and Building Improvement Strategy 1-2.*

TABLE 7.8

Building Energy Performance Summary: Base Case vs. Strategy 1-2

Category of Use	Annual Site Energy Consumptions			
	Basecase	Improved Model	Energy Saved	
	kWh	kWh	kWh	(%)
Area Lights	280	280	0	0.0
Equipment	1497	1497	0	0.0
Space Cooling	1480	1443	37	2.5
Pumps	46	46	0	0.0
Vent Fans	165	160	5	3.0
Domestic Hot Water	1807	1807	0	0.0
Total	**5275**	**5233**	**42**	**0.8**

Figure 7.15 shows the simulated zone temperatures of the improved model as compared to the base case. The impact on the spaces' temperatures were similar to the results of Strategy 1-1, with the exception of the lower right graph of Figure 7.15 where it can be seen that, in general, air temperatures in the attic were further reduced from Strategy 1-1. The peak temperature, which occurred around noon, dropped from 115 ºF to approximately 92 ºF. This was a 3 ºF temperature decrease from the Strategy 1-1. From the lower left and upper right graphs in Figure 7.15, it can be seen that there was little further decrease in temperature in the master bedroom and bedroom-3, in either the daytime or evening, as compared to Strategy 1-1. For the first floor space, the living room's temperatures was not changed, as was the case with

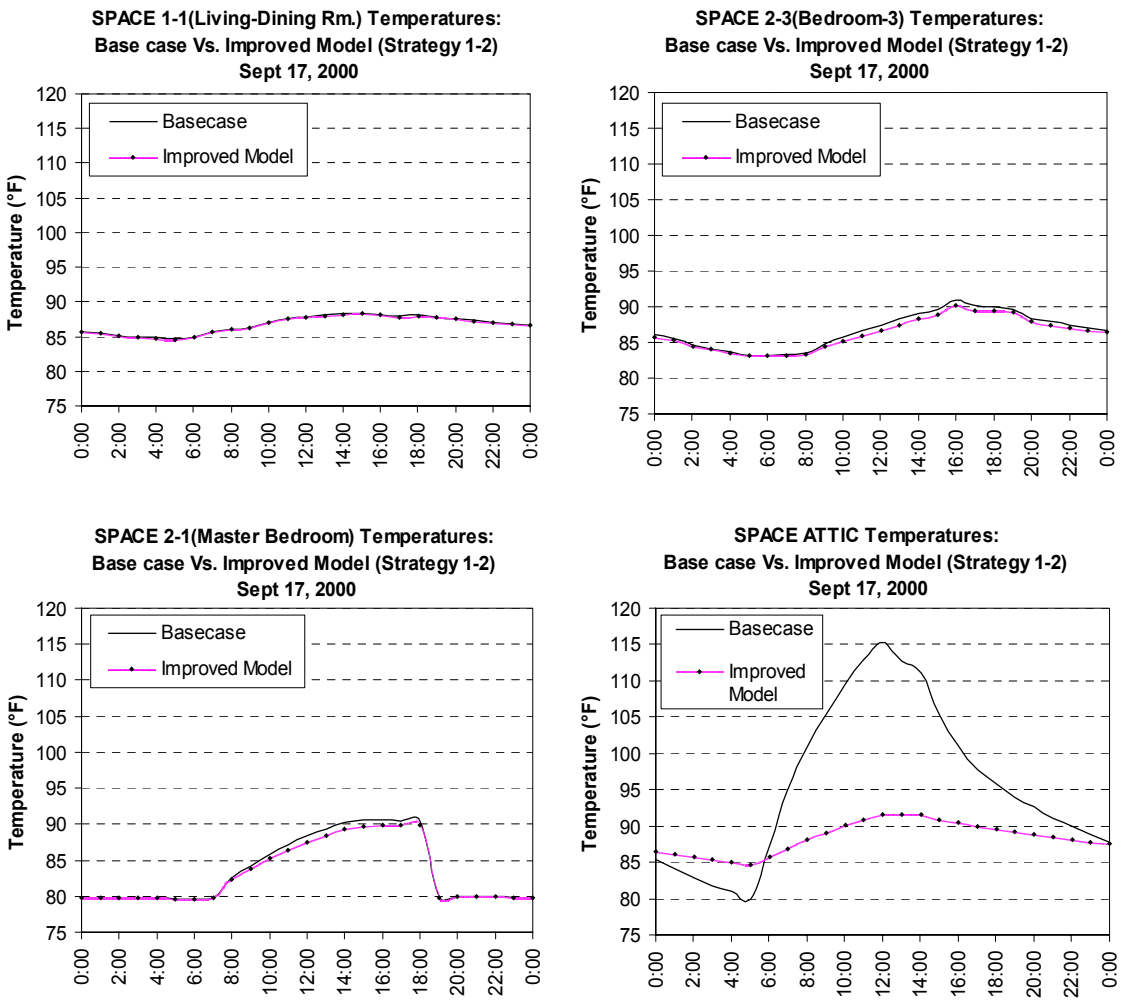


Figure 7.15 *Comparison Between Base Case and Strategy 1-2 Space Temperatures.*

Strategy 1-1 (shown in the upper left graph of Figure 7.15).

The small impact of Strategies 1-1 and 1-2 on the living spaces' temperatures and the building's energy use is probably due to the fact that there already was R-11 fiberglass insulation installed on the second floor ceiling (see Figure 5.2). Installing insulation behind the roof tiles did reduce air temperatures in the attic, but it did not significantly reduce air temperatures in the living spaces or in the building energy use.

7.3.2 Strategy 2: Improve the 2nd Floor Ceiling Insulation

Strategy 2 aimed to increase the heat resistance of the insulation that is placed on the 2nd floor ceiling (upgraded from the existing R-11 to R-28 fiberglass insulation). It was learned from the results of Strategies 1-1 and 1-2 that installing insulation on the back of the roof tiles did not significantly reduce the living spaces' air temperatures or the building's energy use. Strategy 2 was therefore an attempt to see if there was a difference between upgrading the 2nd floor ceiling's insulation and installing insulation on the back of the roof tiles.

Figure 7.16 shows the annual energy use of the improved model entitled Strategy 2, as compared to that of the base case. The BEPS output of the improved model Strategy 2 as compared to the base case is shown in Table 7.9. From Figure 7.16 and Table 7.9, energy use for space cooling and ventilation fans were reduced by 3.3 and 3.0 percent respectively. This resulted in a decrease of total energy consumption by 1 percent, or 54 kWh per year, which had small impact on the cooling energy use, and an even smaller impact on the annual energy use.

Figure 7.17 shows the simulated zone temperatures of the improved model as compared to the base case. The results of the air temperatures in the living spaces (i.e., the master bedroom, bedroom-3, and the living room) were similar to the results of Strategies 1-1 and 1-2. There were small decreases in zone temperatures in the living spaces on the second floor, but not in the living room on the ground floor. However, the temperatures in the attic were totally different from those of Strategies 1-1 and 1-2, as expected. In the lower right graph of the Figure 7.17, it can be seen that in general, air temperatures in the attic increased slightly from the base case, which is probably due to the decrease cooling of the attic by the space below. The peak temperature, which occurred around noon, increase from 115 ºF to approximately 116 ºF. The increase in insulation prevented the cooling from the bedrooms below, thus the attic temperatures rose higher.

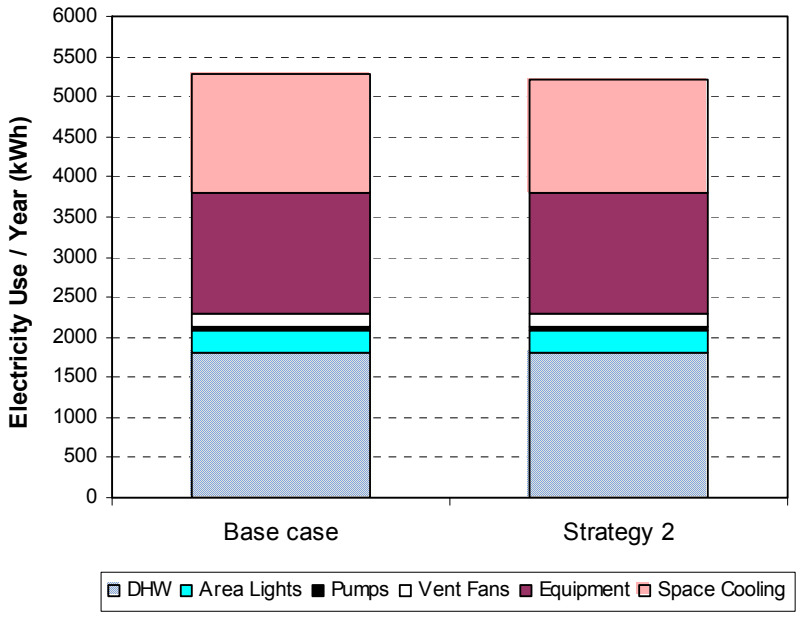


Figure 7.16 *Comparison of Annual Energy Use of the Base Case and Building Improvement Strategy 2.*

TABLE 7.9

Building Energy Performance Summary: Base Case vs. Strategy 2

Category of Use	Annual Site Energy Consumptions			
	Base case	Improved Model	Energy Saved	
	kWh	kWh	kWh	(%)
Area Lights	280	280	0	0.0
Equipment	1497	1497	0	0.0
Space Cooling	1480	1431	49	3.3
Pumps	46	46	0	0.0
Vent Fans	165	160	5	3.0
Domestic Hot Water	1807	1807	0	0.0
Total	**5275**	**5221**	**54**	**1.0**

In summary, from the results of Strategies 1-1, 1-2 and 2, it can be seen that the living spaces' air temperatures and building energy use slightly deceased from the base case. Strategy 2 yielded the highest reduction in building energy use (1 percent) as compared to Strategy 1-1 (0.5 percent) and Strategy 1-2 (0.8 percent).

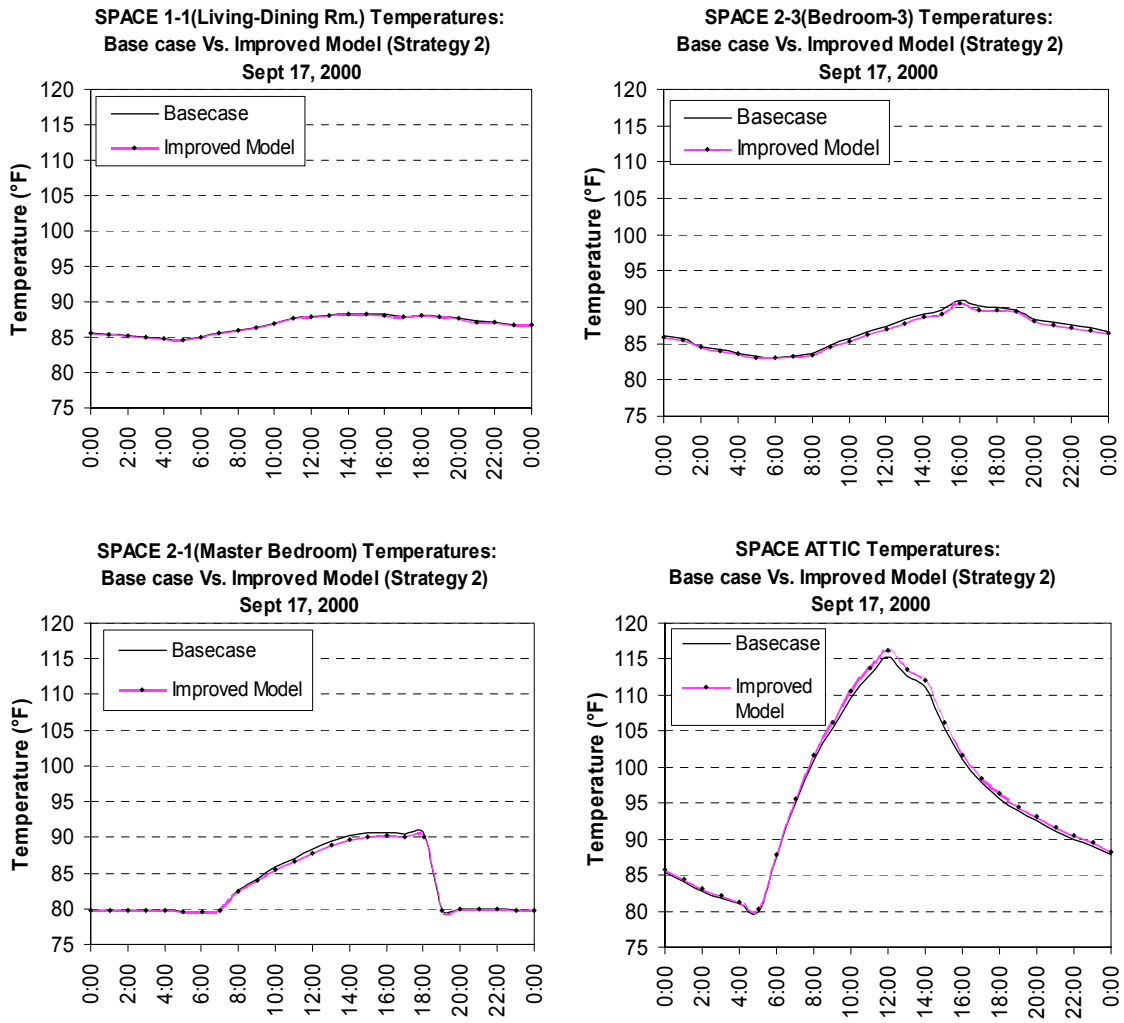


Figure 7.17 *Comparison Between Base Case and Strategy 2 Space Temperatures.*

7.3.3 Strategy 3: Improve Wall Insulation

Strategy 3 was another of the energy efficiency strategies that aimed to improve the case-study building's envelope. The base case's exterior walls were 4-inch brick walls

plastered with cement on both the exterior and interior sides of the walls. Four light-weight concrete wall systems were investigated in this Strategy as described in Table 7.6. The four following sections present the results of each light-weight concrete wall system.

7.3.3.1 Strategy 3-1: 4" (10 cm) Light-weight Concrete Block

Strategy 3-1 replaced the typical 4-inch brick walls, which are used in Thai housing, with light-weight concrete block walls. Light-weight concrete blocks are considered as a new construction material in Thai housing industry. Most walls used in Thai houses are 4-inch brick and concrete block. This strategy endeavored to investigate the impact of light-weight concrete block walls on space temperatures and building energy use of the base case.

Figure 7.18 shows the annual energy use of the improved model Strategy 3-1 as compared to that of the base case. The BEPS of the improved model Strategy 3-1 as compared to the base case is shown in Table 7.10. From Figure 7.18 and Table 7.10, it can be seen that energy used for space cooling and ventilation fans were reduced by 24.5 and 29.1 percent respectively. This resulted in a decrease of total energy consumption by 7.8 percent, or 411 kWh per year.

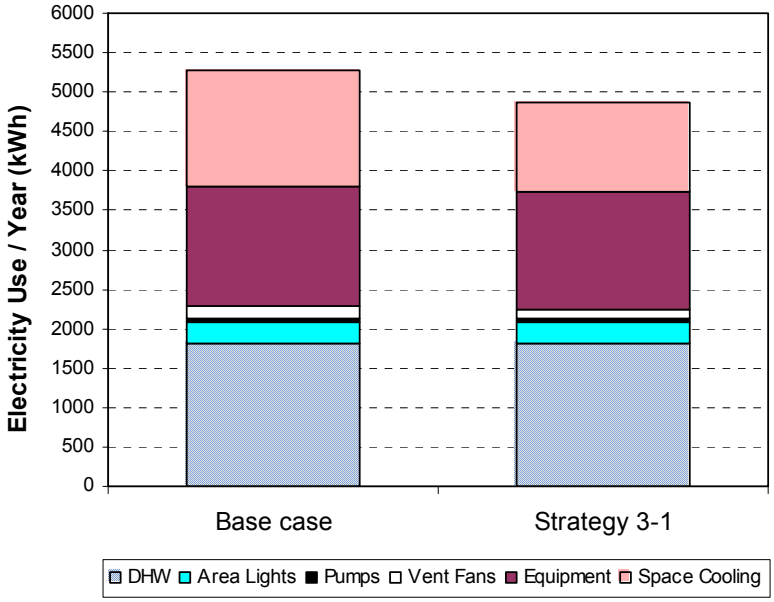


Figure 7.18 *Comparison of Annual Energy Use of the Base Case and Building Improvement Strategy 3-1.*

Figure 7.19 shows the simulated zone temperatures of the improved model as compared to the base-case simulation. From Figure 7.16, it can be seen that, in general, air temperatures in all spaces of the improved model were higher than those of the base case. However, as was mentioned earlier, the BEPS reported a reduction in air conditioning energy use as shown in the Table 7.10. Since there were no other adjustments made, except to the walls on the DOE-2 Strategy 3-1 input file, the reduction of energy consumption by the air conditioning systems occurred because of reduced cooling loads from the walls. One reason for this is that the light-weight concrete block walls store less heat than the 4-inch brick walls. The light-weight concrete had a density of approximately 30 lb/ft^3 as compared to that of to 120 lb/ft^3 of the brick walls (LBNL, 1982 p. X.B.5). Since the A/C is only run in the evenings the light weight walls take less time to cool down and therefore use less cooling energy.

The upper right graph in Figure 7.16 shows the space temperatures of bedroom-3, an unconditioned space. From the graph, the results of the improved model Strategy 3-1 show that the improved model's space temperatures from midnight to 7:00 a.m. were significantly lower than that of the base case. The improved model's space temperatures were also slightly lower than that of the base case from around 10:00 p.m. to 12:00 a.m. Bedroom-3, bedroom-2 and the master bedroom are adjacent spaces on the second floor. Thus, this caused the reduction in energy use of the air conditioning systems, as reported by the BEPS in Table 7.10.

TABLE 7.10

Building Energy Performance Summary: Base Case vs. Strategy 3-1

Category of Use	Annual Site Energy Consumptions			
	Base case	Improved Model	Energy Saved	
	kWh	kWh	kWh	(%)
Area Lights	280	280	0	0.0
Equipment	1497	1497	0	0.0
Space Cooling	1480	1117	363	24.5
Pumps	46	46	0	0.0
Vent Fans	165	117	48	29.1
Domestic Hot Water	1807	1807	0	0.0
Total	**5275**	**4864**	**411**	**7.8**

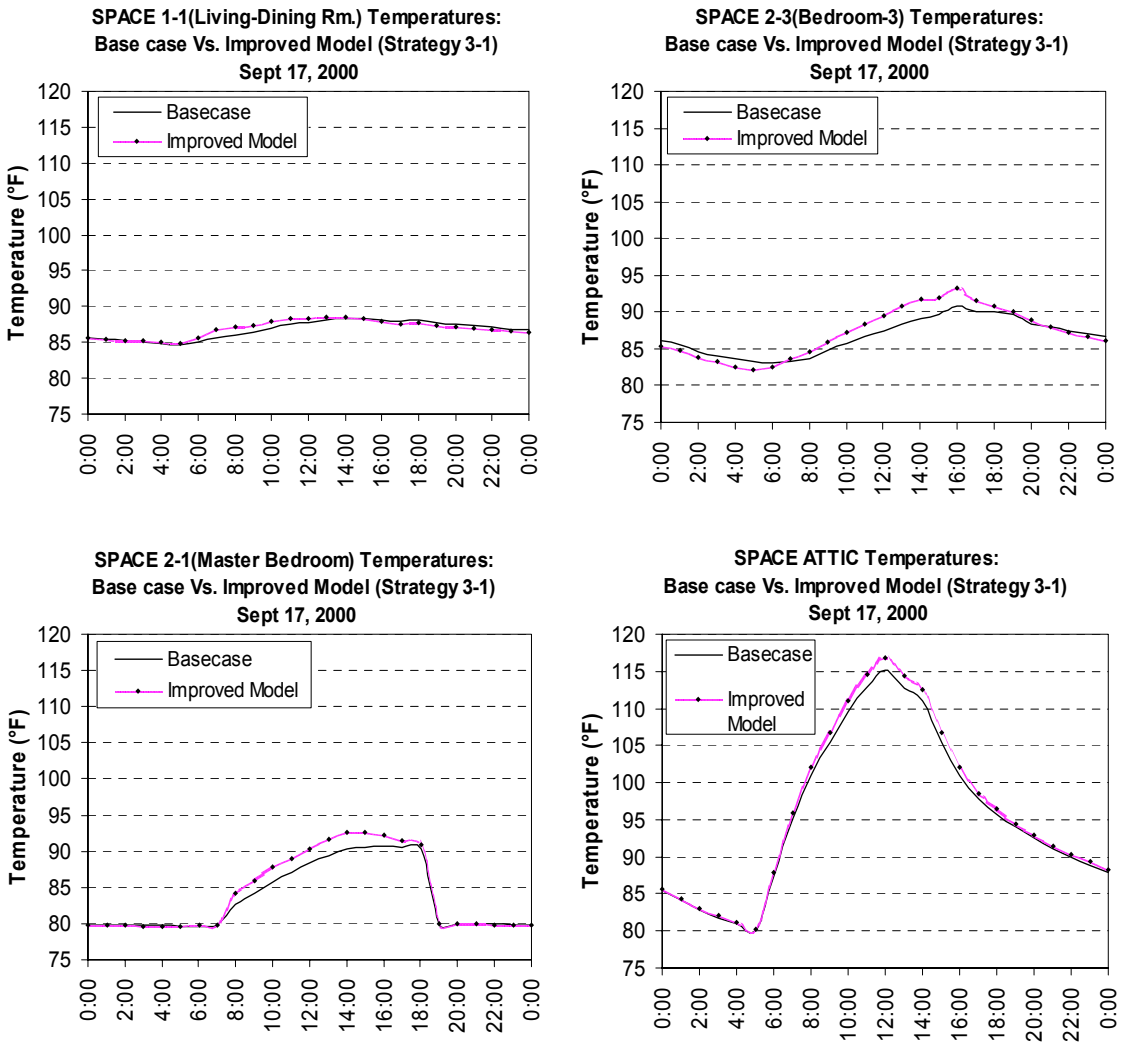


Figure 7.19 *Comparison between Base Case and Strategy 3-1 Space Temperatures.*

7.3.3.2 Strategy 3-2: 6" (15 cm) Light-weight Concrete Block

Strategy 3-2 was similar to Strategy 3-1, with the difference that 6-inch light-weight concrete blocks were used instead of 4-inch light-weight concrete blocks. Increasing the thickness of the walls resulted in higher insulation levels. This strategy investigated the change in the building's energy use and space temperatures from Strategy 3-2.

Figure 7.20 shows the annual energy use of the improved model Strategy 3-2 as

compared to that of the base-case simulation. The BEPS output of the improved model Strategy 3-2 as compared to the base case is shown in Table 7.11. From Figure 7.20 and Table 7.11, it can be seen that the energy used for space cooling and ventilation fans was reduced by 24.8 and 29.7 percent, respectively. This resulted in a decrease of total energy consumption of 7.9 percent or 416 kWh per year. The results from Strategy 3-2 are similar to the results from Strategy 3-1, which had a reduction of 7.8 percent in building energy use. Thus, there was no significant difference in the reduction of the building's energy use by increasing the thickness of the light-weight concrete walls from 4 to 6 inches. The results of the space temperatures, which are shown in Figure 7.21, were also similar to the results obtained from Strategy 3-1.

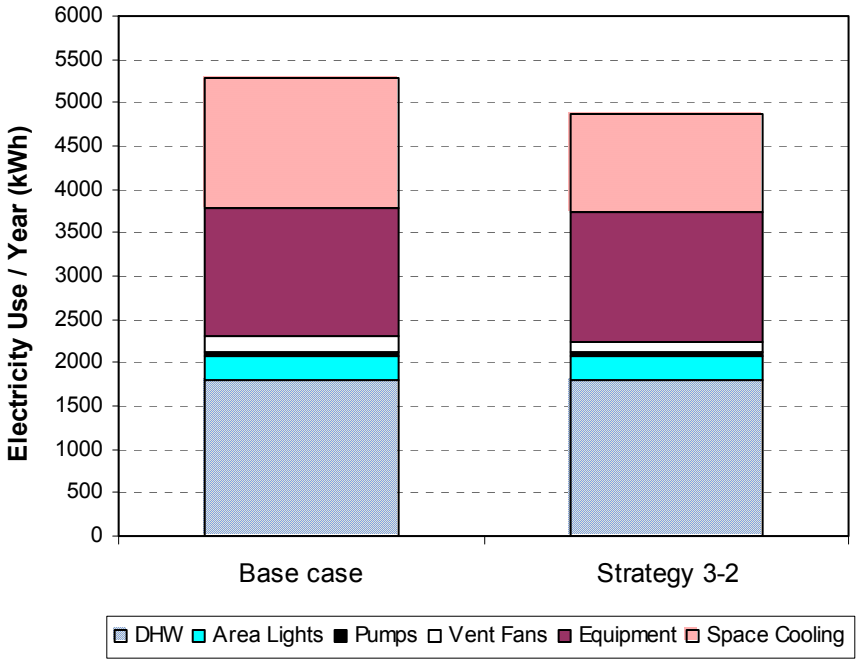


Figure 7.20 *Comparison of Annual Energy Use of the Base Case to Building Improvement Strategy 3-2.*

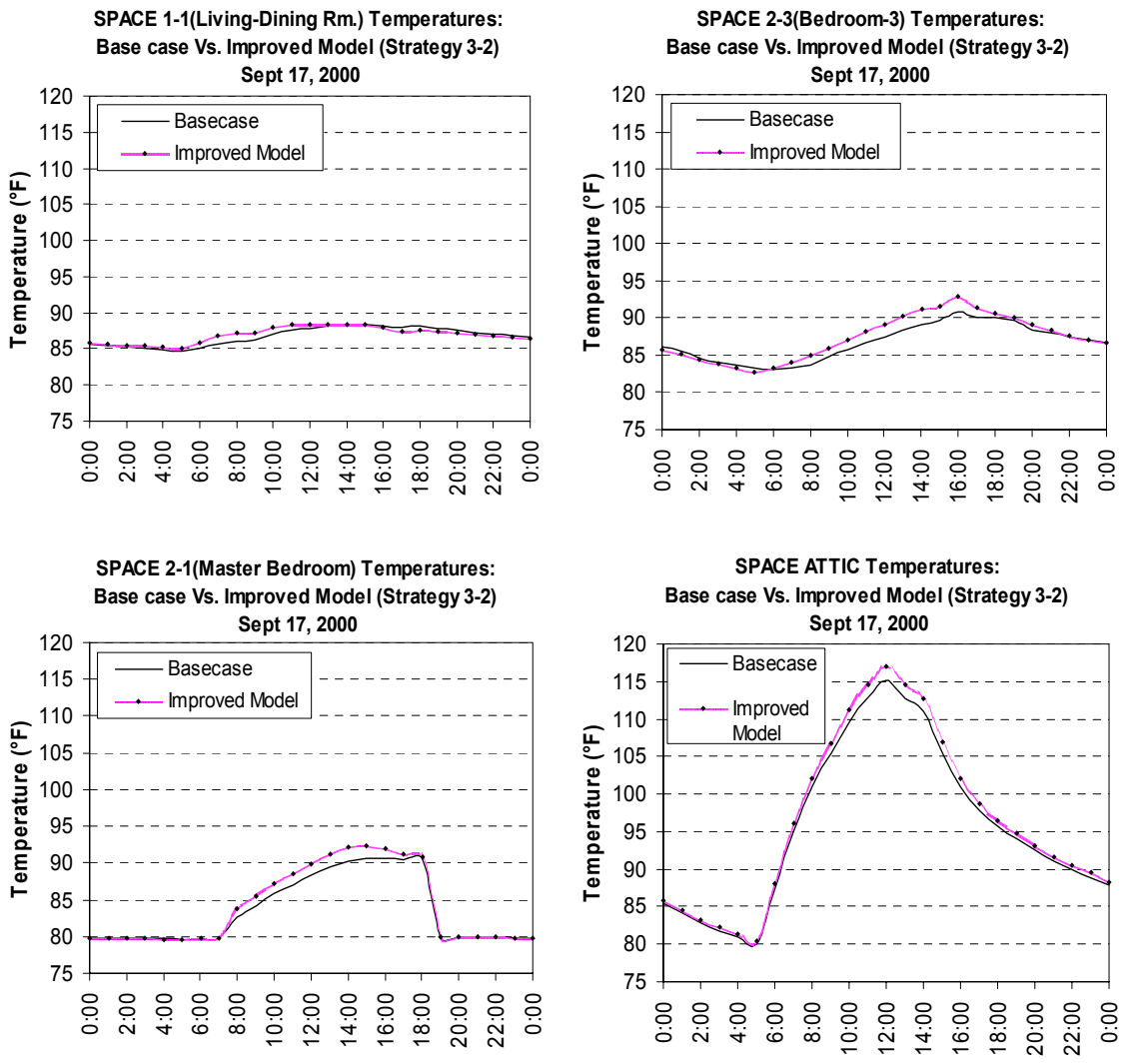


Figure 7.21 *Comparison Between the Base Case and Strategy 3-2 Space Temperatures.*

TABLE 7.11

Building Energy Performance Summary: Base Case vs. Strategy 3-2

Category of Use	Annual Site Energy Consumptions			
	Base case	Improved Model	Energy Saved	
	kWh	kWh	kWh	(%)
Area Lights	280	280	0	0.0
Equipment	1497	1497	0	0.0
Space Cooling	1480	1113	367	24.8
Pumps	46	46	0	0.0
Vent Fans	165	116	49	29.7
Domestic Hot Water	1807	1807	0	0.0
Total	**5275**	**4859**	**416**	**7.9**

7.3.3.3 Strategy 3-3: 4” (15 cm) Light-weight Concrete Block Wall with Exterior Insulation

The results of Strategy 3-1 and 3-2 show the 6-inch light-weight concrete blocks yielded very little difference in space temperatures or building energy use versus the 4-inch wall. Thus, the 4-inch light-weight blocks were used in this strategy to further improve the effectiveness of the wall. Thus, this strategy was similar to Strategy 3-1 except that an insulation layer and siding material were incorporated into the walls. R-10 foam boards (Polystyrene) and non-asbestos fiber cement boards were installed on the exterior side of the wall. Plastic sheets (vapor seal) would be installed between the foam boards and cement boards to block moisture out. The details of the wall’s thermal properties are presented in Appendix D.

Figure 7.22 shows the annual energy use of the improved model Strategy 3-3 as compared to that of the base-case simulation. The BEPS output of the improved model Strategy 3-3 as compared with the base-case simulation is shown in Table 7.12. From Figure 7.22 and Table 7.12, energy used for space cooling and ventilation fans was reduced by 25.6 and 29.7 percent, respectively. This resulted in the decrease of total energy consumption by 8.1 percent, or 428 kWh per year. This was a small improvement from the Strategy 3-1 that saw a 7.8 percent or 411 kWh reduction in annual energy use.

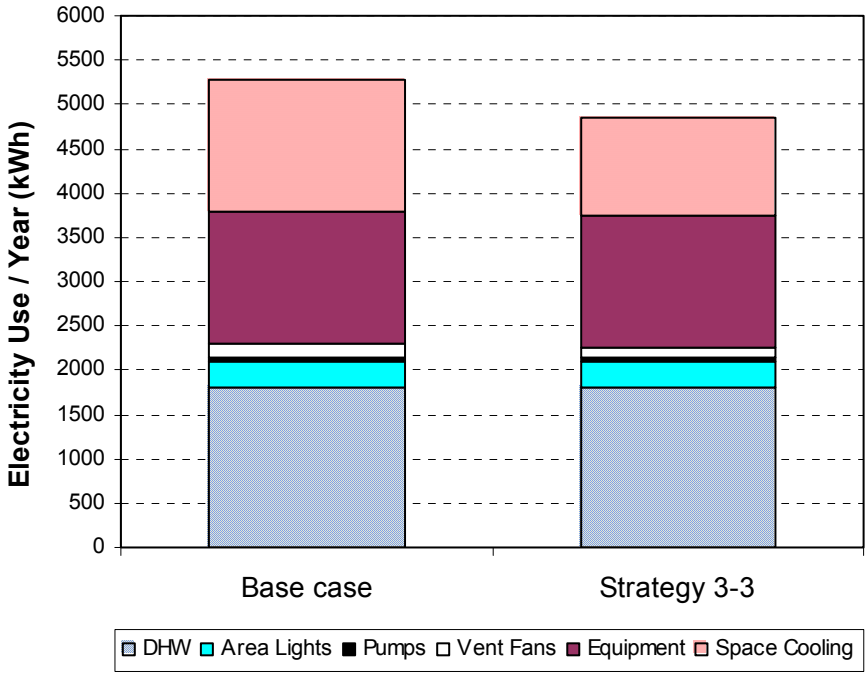


Figure 7.22 *Comparison Between the Annual Energy Use of the Base Case and Building Improvement Strategy 3-3.*

TABLE 7.12

Building Energy Performance Summary: Base Case vs. Strategy 3-3

Category of Use	Annual Site Energy Consumptions			
	Base case	Improved Model	Energy Saved	
	kWh	kWh	kWh	(%)
Area Lights	280	280	0	0.0
Equipment	1497	1497	0	0.0
Space Cooling	1480	1101	379	25.6
Pumps	46	46	0	0.0
Vent Fans	165	116	49	29.7
Domestic Hot Water	1807	1807	0	0.0
Total	**5275**	**4847**	**428**	**8.1**

The space temperatures of Strategy 3-3 are shown in Figure 7.23. The temperatures of the master bedroom and the attic were similar to Strategies 3-2 and 3-1. However, the temperatures in the living room and bedroom-3 were slightly different from Strategies 3-1 and 3-2. The living room temperatures from midnight to 6:00 a.m. were slightly higher than those in the base case, which were different from the results presented by Strategies 3-1 and 3-2. The space temperatures in this period were approximately the same as those in the base case.

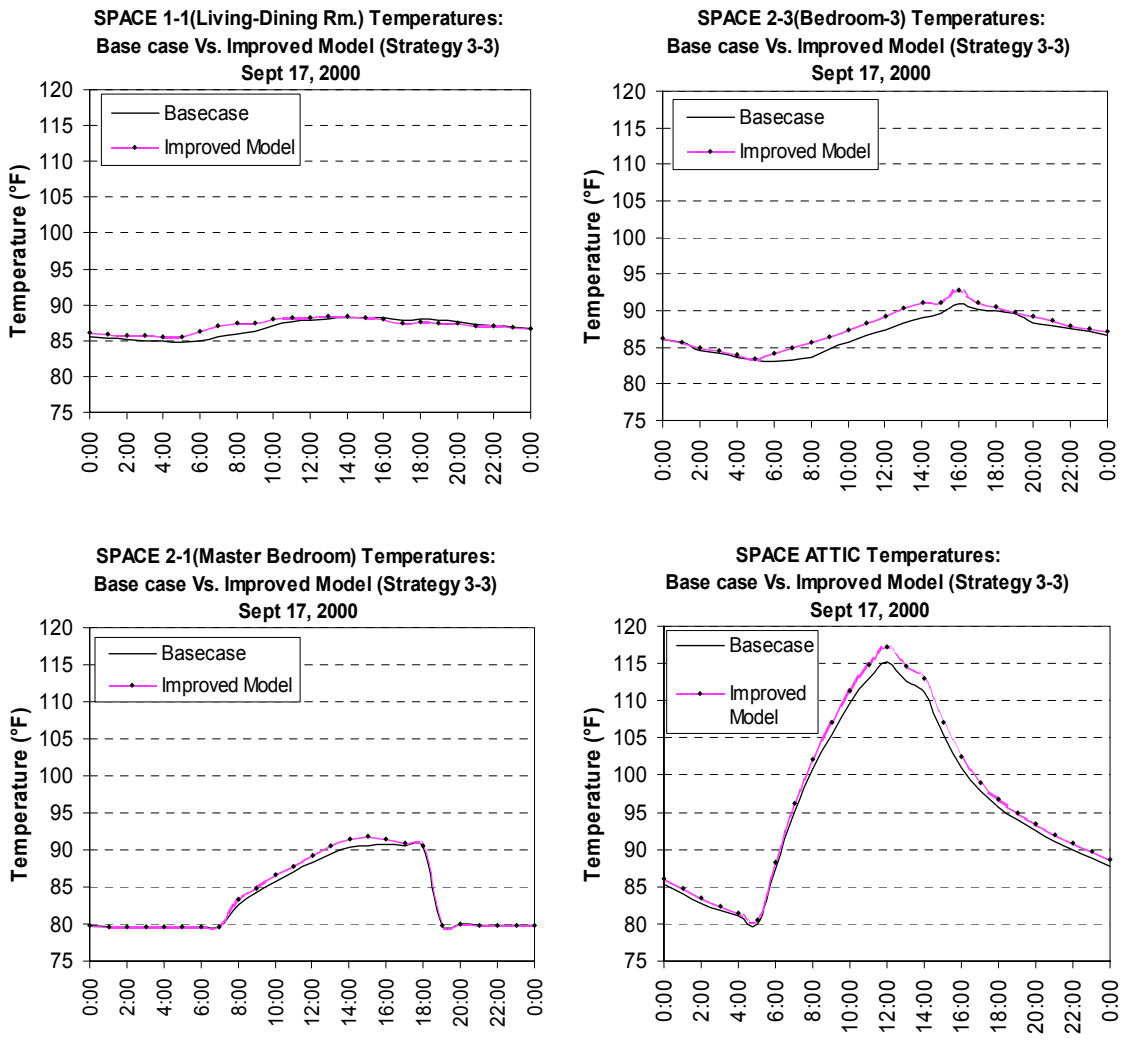


Figure 7.23 *Comparison Between the Base Case and Strategy 3-3 Space Temperatures.*

For bedroom-3, the space temperature profile shifted slightly up from Strategies 3-1, and 3-2. The results of the bedroom-3 temperatures in Strategies 3-1and 3-2 from midnight to 6:00 a.m. were lower than those in the base case, but Strategy 3-3's bedroom-3 temperatures were higher than those in the base case.

In summary, although there was a reduction of building energy use (from the air conditioning systems) that further improved from Strategies 3-1 and 3-2, there were also increases in space temperatures in the living room and bedroom-3. Thus, both of these spaces would actually be less comfortable with Strategy 3-3 during those periods when the A/C system was turned-off.

7.3.3.4 Strategy 3-4: 4" (15 cm) Light-weight Concrete Block Walls with Interior Insulation

Strategy 3-4 was similar to Strategy 3-3, but the wall's insulation was located in the interior. The siding material that was used in Strategy 3-3 was not necessary, since the insulation was inside. Gypsum boards were used as an interior finishing material, which covered the insulation layer. This strategy was performed in order to investigate the effects of interior insulation on the building's energy consumption and space temperatures, as compared to Strategy 3-3 which had the insulation on the exterior side.

Figure 7.24 shows the annual energy use of the improved model entitled Strategy 3-4, as compared to that of the base case. The BEPS output of the improved model Strategy 3-4, as compared to the base case is shown in Table 7.13. From Figure 7.24 and Table 7.13, it can be seen that the energy used for space cooling and ventilation fans was reduced by 28.6 and 33.3 percent, respectively. This resulted in a decrease of total energy consumption by 9.1 percent, or 479 kWh per year. The results of Strategy 3-3 show that it can reduce the annual energy consumption by 8.1 percent. Thus Strategy 3-4 can save one percent more of the building's energy use than Strategy 3-3.

The results of the space temperatures were similar to the results from Strategy 3-3. There were temperature increases during those periods when the A/C was turned-off in all spaces as compared to the base case's temperatures as shown in Figure 7.25.

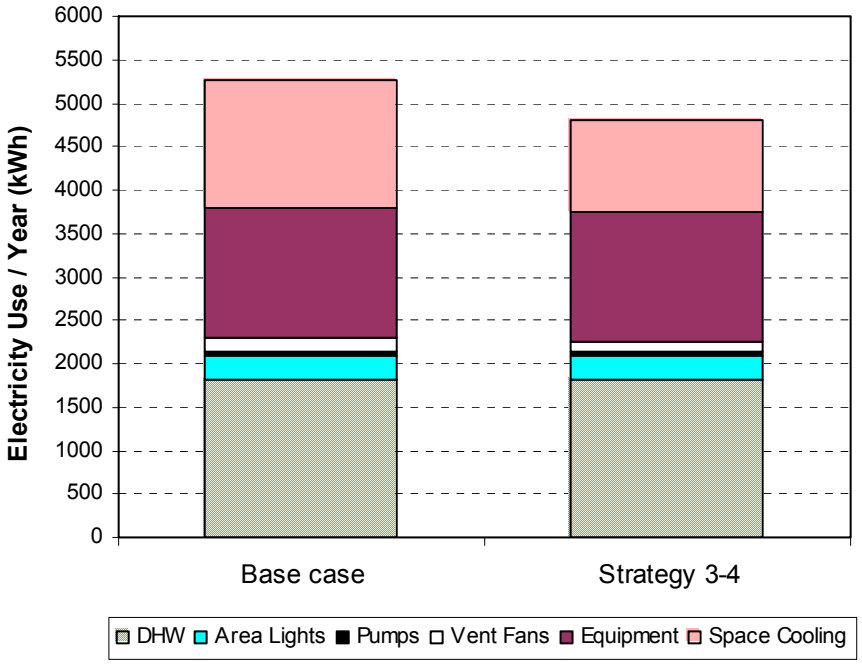


Figure 7.24 *Comparison of the Annual Energy Use of the Base Case and Building Improvement Strategy 3-4.*

TABLE 7.13

Building Energy Performance Summary: Base Case vs. Strategy 3-4

Category of Use	Annual Site Energy Consumptions			
	Base case	Improved Model	Energy Saved	
	kWh	kWh	kWh	(%)
Area Lights	280	280	0	0.0
Equipment	1497	1497	0	0.0
Space Cooling	1480	1056	424	28.6
Pumps	46	46	0	0.0
Vent Fans	165	110	55	33.3
Domestic Hot Water	1807	1807	0	0.0
Total	**5275**	**4796**	**479**	**9.1**

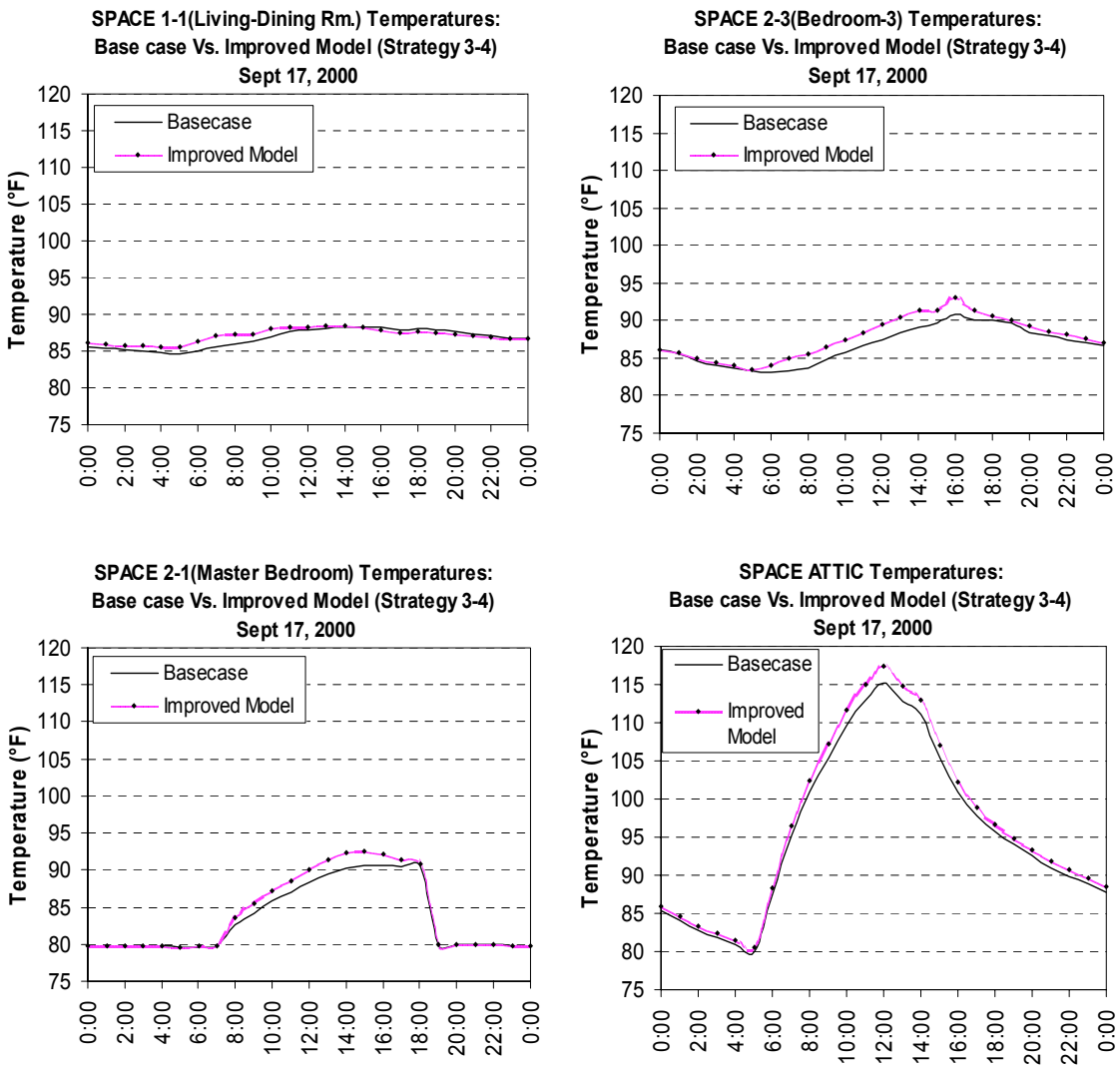


Figure 7.25 *Comparison Between the Base Case and Strategy 3-4 Space Temperatures.*

7.3.4 Strategy 4: Low-E Windows

Strategy 4 was one of the energy efficiency strategies that aimed to improve the building's envelope. Single-pane clear glass windows with wooden frames were replaced with double-glazed Low-E glass windows with thermal-break aluminum frames. Both the thermal and the optical performance of the Low-E windows are an improvement over that of single-pane clear glass. Double-pane windows with inert gas (argon) between the panes have a greater

insulating value (R-value) than the existing windows. The Low-E coating on the inside of the outdoor pane of glass selectively transmits the sun's visible light (short-wave radiation) while reflecting a majority of radiant heat (long-wave infrared radiation) (Ander, G., 1995).

Figure 7.26 shows the annual energy use of the improved model entitled Strategy 4 as compared to that of the base-case simulation. The BEPS output of the improved model Strategy 4 as compared to the base case is shown in Table 7.14. From Figure 7.26 and Table 7.14, it can be seen that the energy used for space cooling and ventilation fans was increased by 0.5 and 0.6 percent, respectively. This resulted in an increase of total energy consumption by 0.2 percent, or 9 kWh per year.

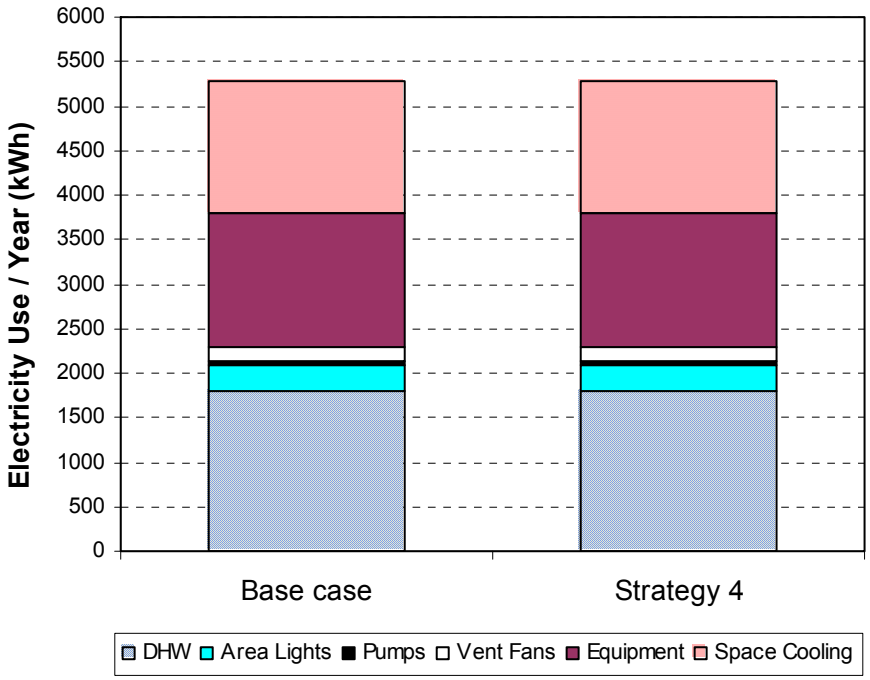


Figure 7.26 *Comparison of the Annual Energy Use of the Base Case and Building Improvement Strategy 4.*

TABLE 7.14

Building Energy Performance Summary: Base Case vs. Strategy 4

Category of Use	Annual Site Energy Consumptions			
	Base case	Improved Model	Energy Saved	
	kWh	kWh	kWh	(%)
Area Lights	280	280	0	0.0
Equipment	1497	1497	0	0.0
Space Cooling	1480	1488	-8	-0.5
Pumps	46	46	0	0.0
Vent Fans	165	166	-1	-0.6
Domestic Hot Water	1807	1807	0	0.0
Total	**5275**	**5284**	**-9**	**-0.2**

However, it can be seen from Figure 7.27 that the temperatures in the living spaces, where the Low-E windows were installed, decreased in the daytime, especially the temperatures in the living room where there was a large area of glass on the south wall (see Figure 5.11). Living room temperatures actually decreased in the nighttime as well, but to a smaller degree when compared to the daytime. This was probably because there was less heat stored in the space (i.e., in the concrete floor and walls) in the daytime. Thus, there was less heat released during the nighttime when the outdoor temperature was lower than the living room temperature.

As previously mentioned, the energy used by the air conditioning system actually slightly increased due to the change of windows. This was because the Low-E windows effectively decreased heat gain through windows in the daytime, but the air conditioning systems were only operated during the nighttime. Thus, the air conditioning systems did not benefit from the Low-E windows, since the cooling load was not reduced. Figure 7.28 shows the DOE-2 report of heat gains through the south facing window of the master bedroom. In Figure 7.28, the results of the base-case windows (i.e., single-pane window) are compared to the results of Strategy 4 (double-pane Low-E window).

During the daytime, from 7:00 a.m. to 6:00 p.m., the Low-E window performed better than the single-pane window; the total heat gain through the Low-E window was lower than that of the single-pane window, especially at the time of peak load (i.e., 1:00 p.m.). There was a heat gain at the rate of approximately 330 Btu/h through the single-pane window, while there

was a heat gain at the rate of approximately 150 Btu/h through the Low-E window. This shows that the Low-E window can reduce heat gain by approximately 55 percent during the peak load time.

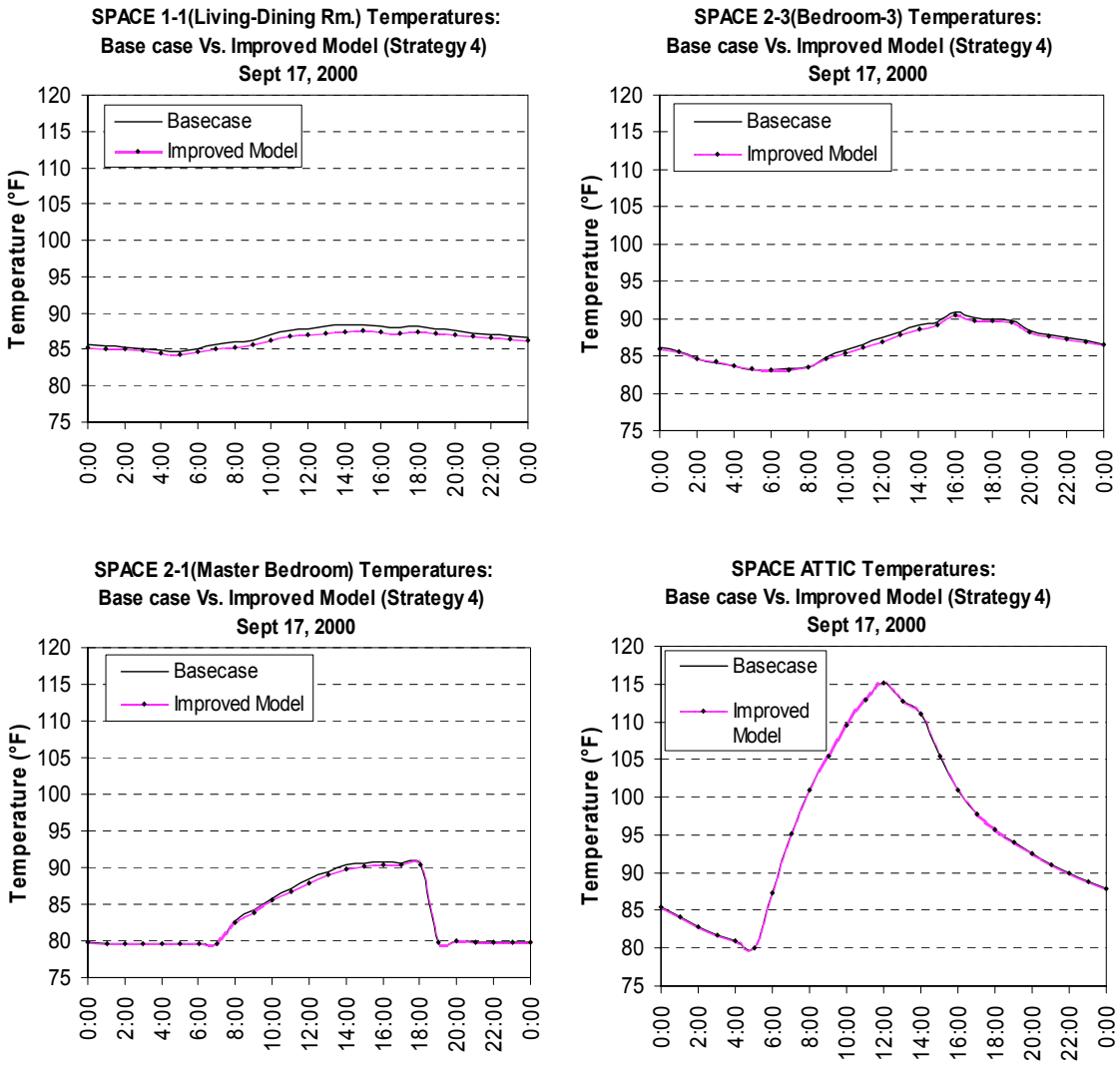


Figure 7.27 *Comparison Between the Base Case and Strategy 4 Space Temperatures.*

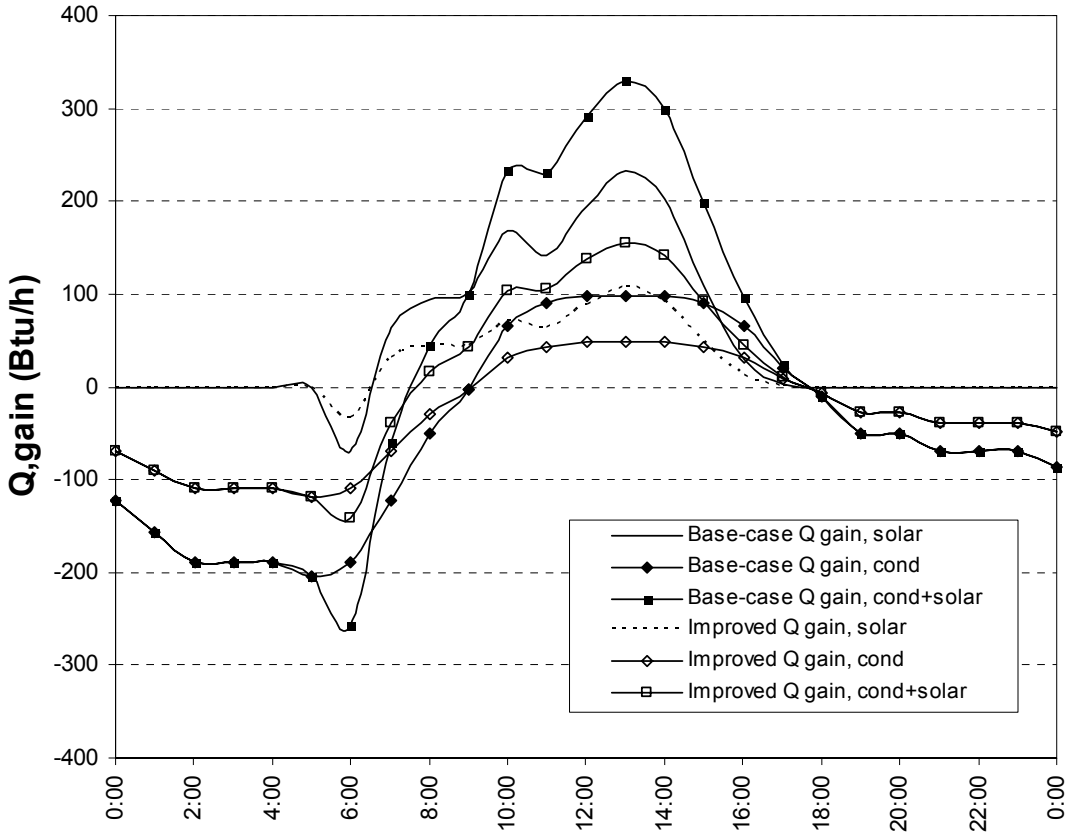


Figure 7.28 *Comparison Between the Base Case and Strategy 4 Heat Gains through the Unshaded South Facing Window of Space 2-1.*

During the nighttime there was no solar radiation and thus the total heat gain/loss was equal to the conductive heat gain/loss. From Figure 7.25, it can be seen that from 6:00 p.m. to approximately 7:00 a.m., there was more heat lost from the single-pane window than from the double-pane Low-E window. This is because the ambient temperatures were lower than the master bedroom temperatures during those periods. From Figure 7.11, it can be seen that the ambient temperatures from midnight to 7:00 a.m. ranged of 75 ºF to 80 ºF (mostly below 77.5 ºF) while the room temperature was around 78.8 ºF (the thermostat set-point temperature). Thus, the ambient temperatures were lower than the room temperatures. This caused a heat loss from the space to the environment. Double-pane Low-E glass, which has higher heat resistance than single-pane glass, allowed the heat to be transmitted at the lower rate. Thus, there was more heat lost from the base-case window than from Strategy 4.

In summary, Low-E windows reduced space temperatures during the daytime. Thus, their use could help improve thermal comfort conditions in these spaces. However, during the nighttime, there are periods when the ambient temperatures were lower than the room temperatures of the conditioned spaces. In this situation, Low-E windows transmitted less heat to the environment than the single-pane windows. Thus, there was a higher cooling load on the air conditioning system, because the inside temperature of the single-pane window would have been lower than the double-pane window. However, there was only a 0.2 percent increase in the energy consumption of the air conditioning system.

7.3.5 Strategy 5: Shading Devices on Windows

In Strategy 5 shading devices were installed on all windows except the north facing windows and those windows that were already shaded, such as the windows that opened to the garage. In the simulation a shading device for a window comprised of one horizontal fin and two vertical fins. Horizontal fins were also installed as "building shades". They were placed between the two pillars that were situated in front of the living room and the master bedroom. These fins were used to block solar radiation to the two spaces that had large areas of glass (glass doors) on the south walls. The details of the shading devices (i.e., the DOE-2 input data) are presented in Appendix D.

Figure 7.29 shows the annual energy use of the improved model for Strategy 5, as compared to that of the base-case simulation. The BEPS output of the improved model Strategy 5 as compared to the base case is shown in Table 7.15. From Figure 7.29 and Table 7.15, it can be seen that the energy used for space cooling and ventilation fans decreased by 1.7 and 1.8 percent, respectively. This resulted in a decrease of total energy consumption by 0.5 percent, or 28 kWh per year.

For the space temperatures, it can be seen from Figure 7.30 that the shading devices slightly decreased the master bedroom and bedroom-3 space temperatures in the daytime. This caused a reduction of 0.5 percent in the energy consumption by the air conditioning systems which were operated during the nighttime. Therefore, there was actually a small reduction in the cooling loads due to the shading devices. Figure 7.31 shows that the heat gained through the window was lowered if the shading devices were installed. At the peak load time of 1:00 p.m., heat was gained at the rate of approximately 330 Btu/h through the window without the shading device, while heat was gained at the rate of approximately 200 Btu/h through the

window with the shading device. This shows that shading devices can reduce the heat gains by approximately 40 percent during the peak load times. However, at the case-study house, since the air conditioning systems were only run in the evenings, this had a small effect on reducing the electricity use.

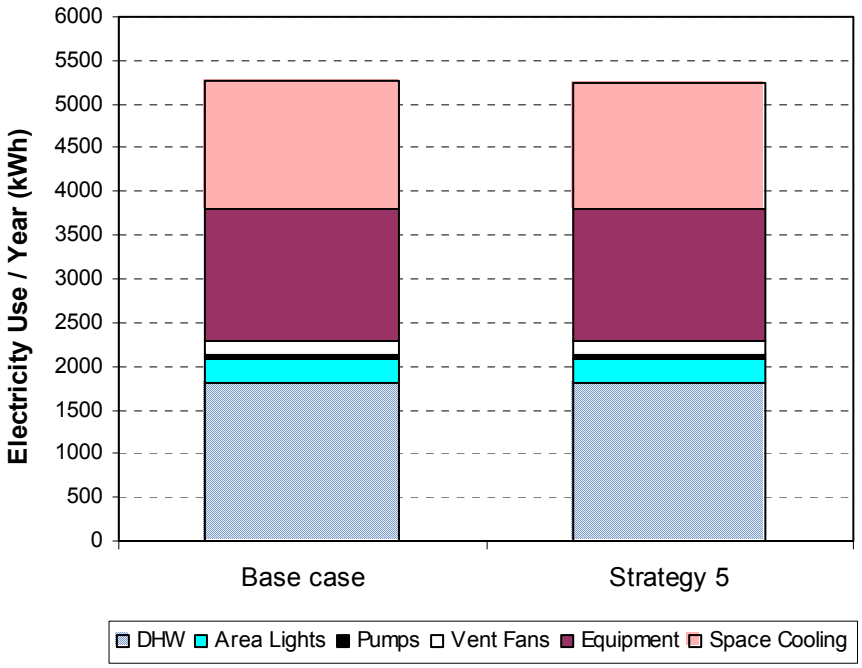


Figure 7.29 *Comparison of the Annual Energy Use of Base Case and Building Improvement Strategy 5.*

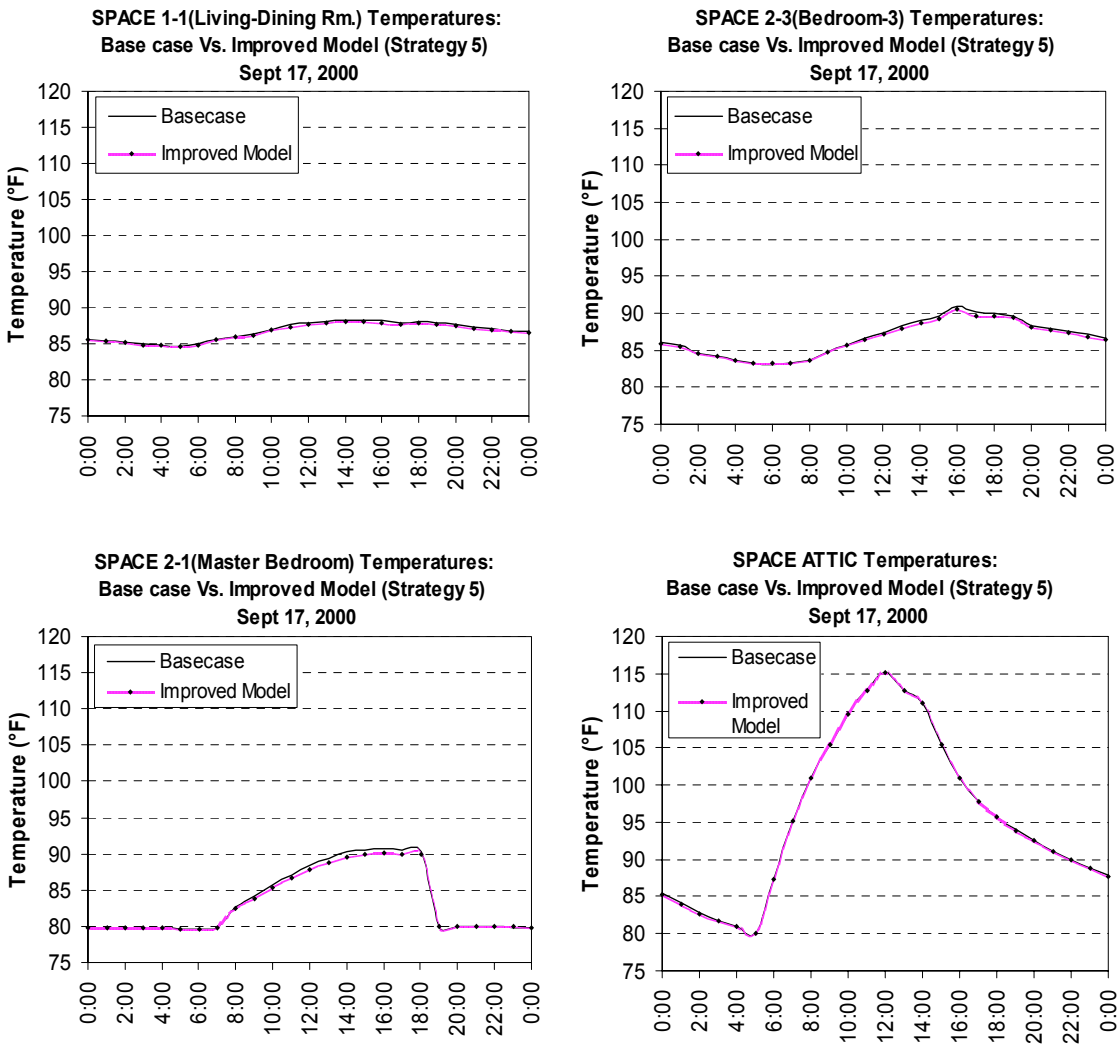


Figure 7.30 *Comparison Between the Base Case and Strategy 5 Space Temperatures.*

TABLE 7.15

Building Energy Performance Summary: Base Case vs. Strategy 5

Category of Use	Annual Site Energy Consumptions			
	Base case	Improved Model	Energy Saved	
	kWh	kWh	kWh	(%)
Area Lights	280	280	0	0.0
Equipment	1497	1497	0	0.0
Space Cooling	1480	1455	25	1.7
Pumps	46	46	0	0.0
Vent Fans	165	162	3	1.8
Domestic Hot Water	1807	1807	0	0.0
Total	**5275**	**5247**	**28**	**0.5**

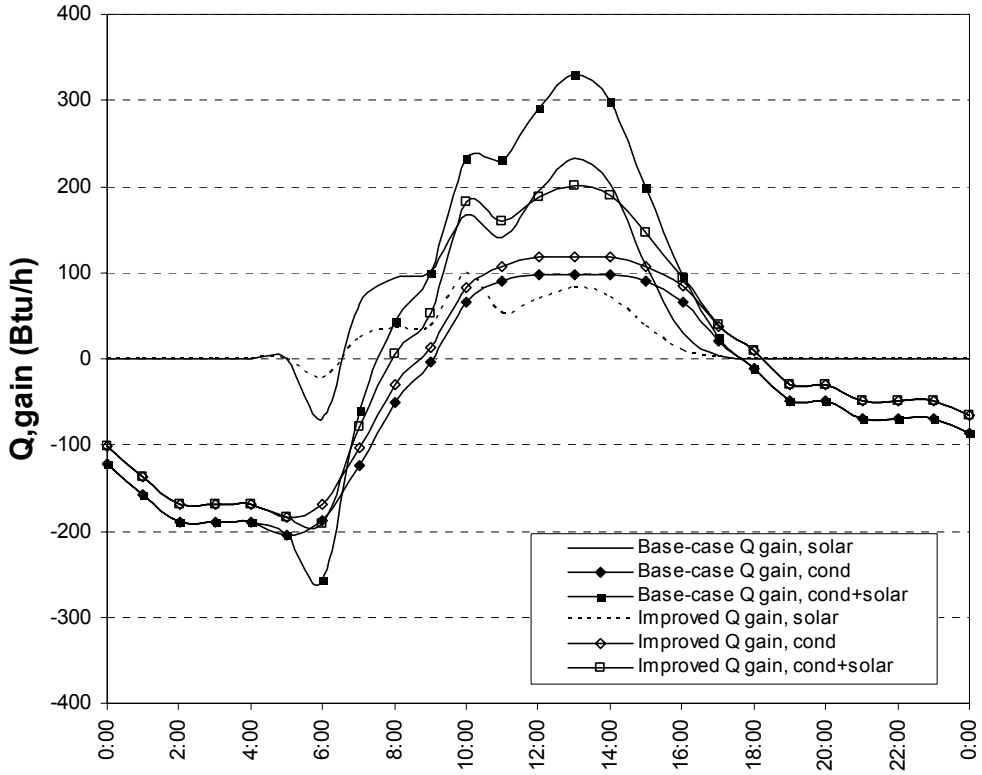


Figure 7.31 *Comparison Between the Base Case and Strategy 5 Heat Gain Through the South Facing Window of Space 2-1.*

7.3.6 Strategy 6: High Thermal Mass Walls

In the study of the thermal conditions in old and new temples in Thailand by Sreshthaputra (2003) it was found that the old Thai temples that had high thermal mass brick walls (2.5 ft. of thickness), which provided lower annual average indoor temperatures than newer temples that were constructed with 4-inch brick walls. Thus, Strategy 6 aimed to investigate the effects of high thermal mass walls on space temperatures, as well as building energy uses in the case-study house.

The case-study house's walls were constructed with 4-inch bricks. In this study, eight-inch and twelve-inch bricks were investigated (i.e., the walls were 2 and 3 times thicker than the base case). Sections 7.3.6.1 and 7.3.6.2 present the results of the eight-inch and twelve-inch walls, respectively.

7.3.6.1 Strategy 6-1: High Thermal Mass Wall (8" Brick)

Figure 7.32 shows the annual energy use of Strategy 6-1, as compared to that of the base-case simulation. The BEPS output of Strategy 6-1 as compared to the base case is shown in Table 7.16. From Figure 7.32 and Table 7.16, it can be seen that the energy used for space cooling and ventilation fans increase by 3.5 and 7.3 percent, respectively. This resulted in an increase of total energy consumption by 1.2 percent, or 64 kWh per year.

For space temperatures, the daily temperature profiles of the living spaces significantly changed from those of the base case. From Figure 7.33 it can be seen that, in general, the living space temperatures in the daytime decreased, which is in contrast to the nighttime space temperatures that increased. The changes were more obvious in the second floor spaces (i.e., the master bedroom and bedroom-3).

For the living room, which was on the ground floor, there was a slight increase of room temperature (approximately 0.5 ºF) from midnight to 9:00 a.m. From 9:00 a.m. to 7:00 p.m., Strategy 6-1's space temperatures were slightly lower (approximately 1 ºF) than those of the base-case simulation. After 7:00 p.m., space temperatures in Strategy 6-1 and the base-case simulation did not differ.

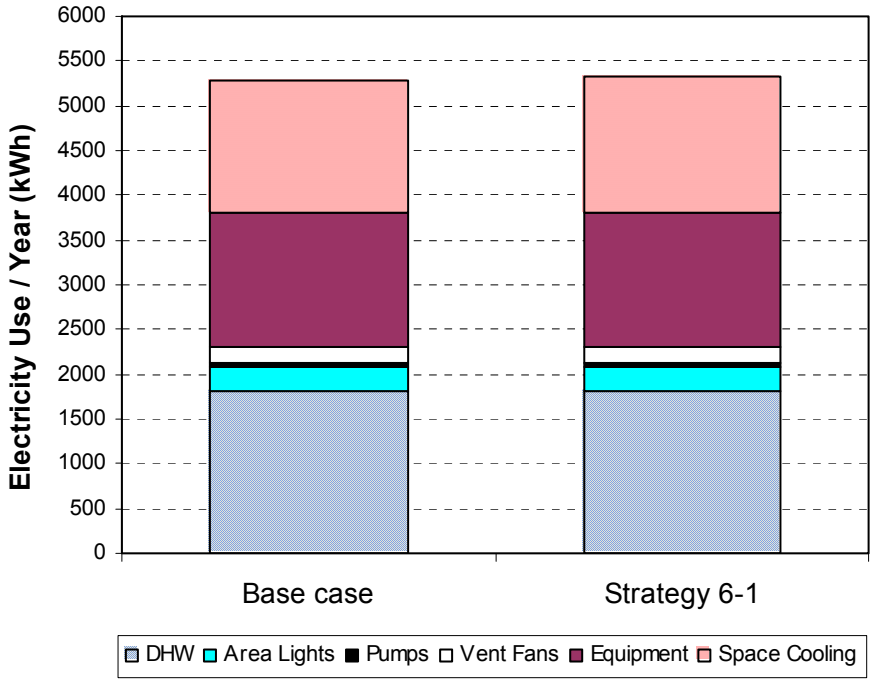


Figure 7.32 *Comparison of the Annual Energy Use of the Base Case and Building Improvement Strategy 6-1.*

TABLE 7.16

Building Energy Performance Summary: Base Case vs. Strategy 6-1

Category of Use	Annual Site Energy Consumptions			
	Base case	Improved Model	Energy Saved	
	kWh	kWh	kWh	(%)
Area Lights	280	280	0	0.0
Equipment	1497	1497	0	0.0
Space Cooling	1480	1532	-52	-3.5
Pumps	46	46	0	0.0
Vent Fans	165	177	-12	-7.3
Domestic Hot Water	1807	1807	0	0.0
Total	**5275**	**5339**	**-64**	**-1.2**

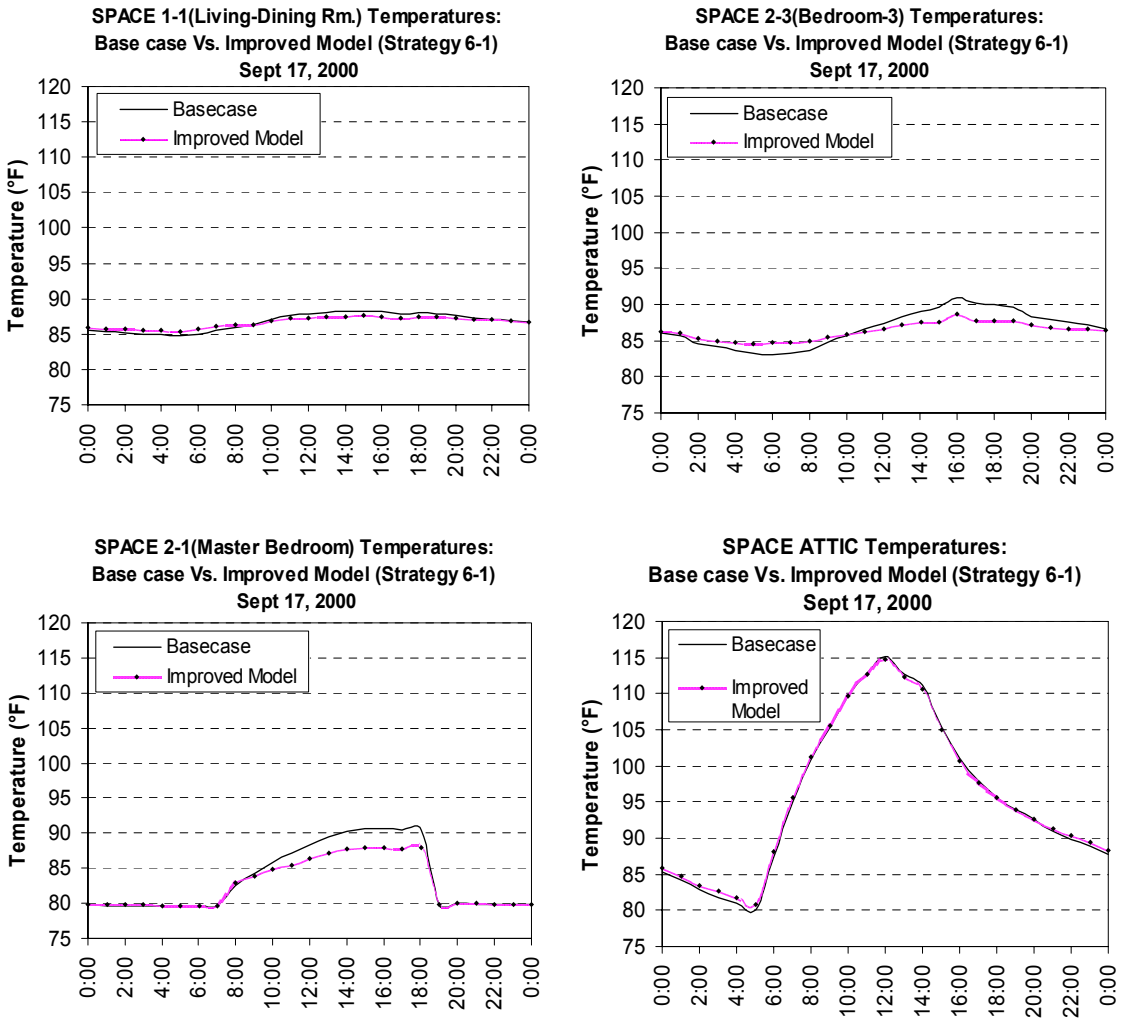


Figure 7.33 *Comparison Between the Base Case and Strategy 6-1 Space Temperatures.*

For the master bedroom and bedroom-3, space temperatures in Strategy 6-1 were higher than those of the base case from midnight to 10:00 a.m. The increase of temperatures was at its peak from 5:00 to 7:00 a.m., when there was a temperature difference of approximately 2 ºF. The change in temperatures during this period could be seen only in bedroom-3's graph, since the master bedroom was conditioned during this period. In the daytime, however, there was a significant decrease in the master bedroom and bedroom-3's space temperatures. For bedroom-3, Strategy 6-1's space temperatures were lower than those of the base case, from 10:00 a.m. to

midnight. The decrease of temperatures was at its peak from 4:00 to 7:00 p.m., when there was a temperature difference of approximately 3 ºF. For the master bedroom, the space temperatures were also significantly decreased from those of the base case, from 9:00 a.m. to 6:00 p.m. The decrease of temperatures was at its peak in the afternoon (from 2:00 to 6:00 p.m.) when there was a temperature difference of approximately 3 to 3.5 ºF. Attic temperatures increased slightly during the nighttime from those of base case. In general, the high thermal mass walls which were below the attic did not affect attic temperatures.

In summary, a high thermal mass wall caused an increase in the building's energy use through the air conditioning system, since nighttime space temperatures were increased because the thermal mass captured more of the daytime heating, which the air conditioning systems then needed to remove during the evening. However, there was a significant decrease in space temperatures especially in the second floor spaces. Thus, a high thermal mass wall can improve comfort conditions during the daytime, however it increased air conditioning load in the simulated case-study house.

7.3.6.2 Strategy 6-2: High Thermal Mass Wall (12" Brick)

Figure 7.34 shows the annual energy use of Strategy 6-2 as compared to that of the base-case simulation. The BEPS output of Strategy 6-2 as compared with the base case is shown in Table 7.17. From Figure 7.34 and Table 7.17, it can be seen that the energy used for space cooling and ventilation fans increased by 0.4 and 3.0 percent respectively. This resulted in an increase of total energy consumption by 0.2 percent, or 11 kWh per year.

Figure 7.35 shows the results of the Strategy 6-2's space temperatures as compared to those of the base-case simulation. The results show that the Strategy 6-2 space temperatures were very similar to the results of Strategy 6-1, showing a slightly larger decrease in the master bedroom's temperatures in Strategy 6-2. The master bedroom's peak temperatures, which occurred from 3:00 p.m. to 6:00 p.m., were reduced by approximately 4 ºF, while there was a decrease in the peak temperature of 3-3.5 ºF in Strategy 6-1.

The results of Strategy 6-1 and 6-2 show that, in case-study house, the high thermal mass walls did not reduce the building's energy use. However, they could significantly improve the daytime thermal comfort in these spaces especially in the second floor spaces. Eight-inch

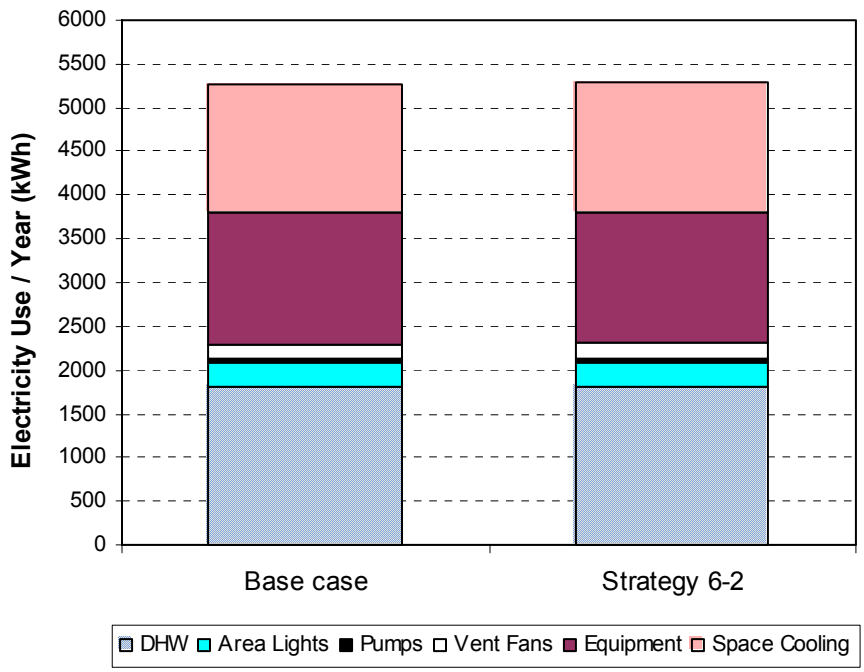


Figure 7.34 *Comparison of the Annual Energy Use of the Base Case and Building Improvement Strategy 6-2.*

TABLE 7.17

Building Energy Performance Summary: Base Case vs. Strategy 6-2

Category of Use	Annual Site Energy Consumptions			
	Base case	Improved Model	Energy Saved	
	kWh	kWh	kWh	(%)
Area Lights	280	280	0	0.0
Equipment	1497	1497	0	0.0
Space Cooling	1480	1486	-6	-0.4
Pumps	46	46	0	0.0
Vent Fans	165	170	-5	-3.0
Domestic Hot Water	1807	1807	0	0.0
Total	**5275**	**5286**	**-11**	**-0.2**

and twelve-inch brick walls yielded similar results for the building's energy use and space temperatures, with the twelve-inch wall showing the largest effect.

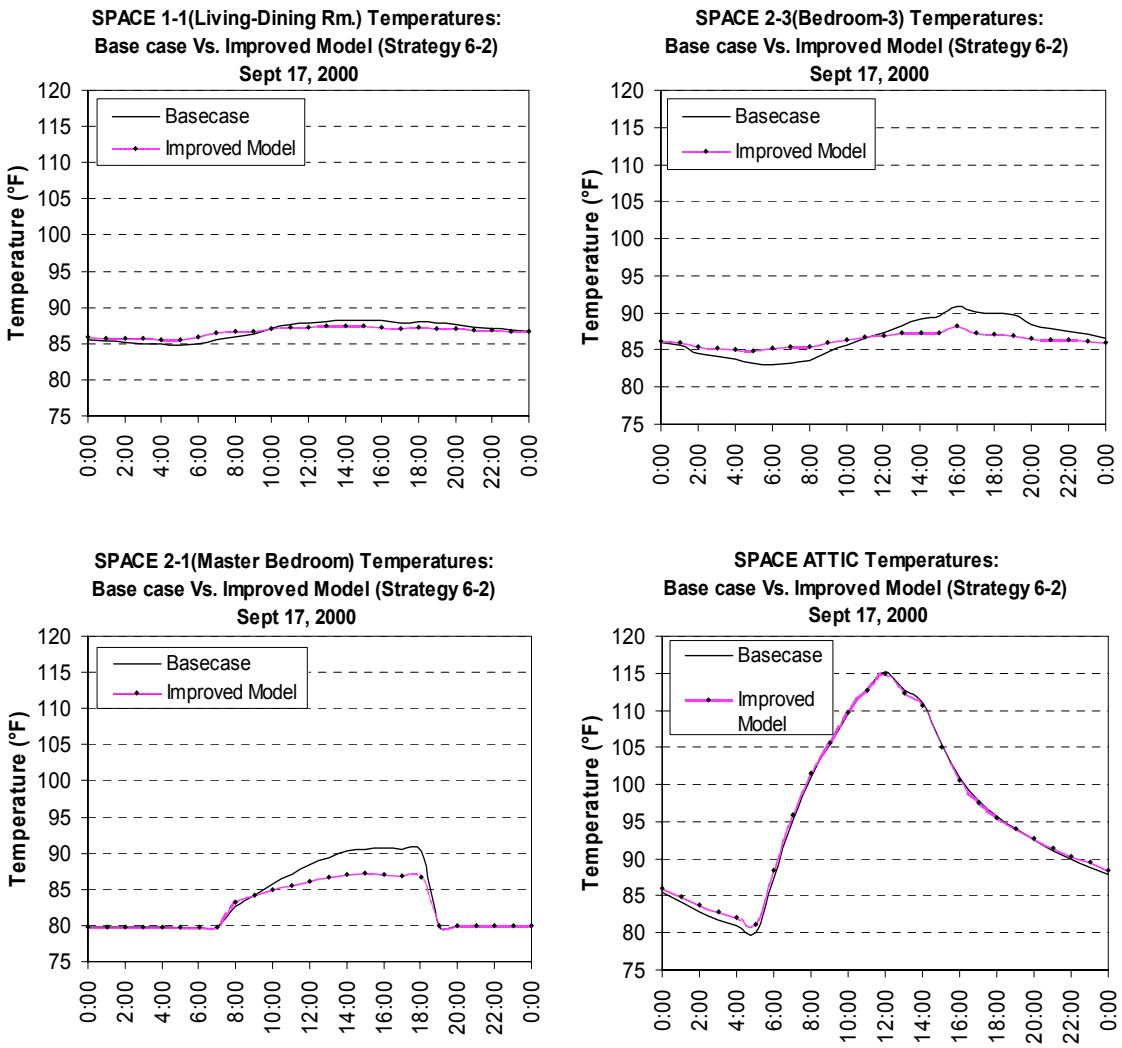


Figure 7.35 *Comparison Between the Base Case and Strategy 6-2 Space Temperatures.*

7.3.7 Strategy 7: Efficient Air Conditioning Systems

This strategy aimed to improve the building's air conditioning systems. Energy use by the air conditioning systems in the base-case house accounted for approximately 30 percent of the total building's energy use. Existing SEER-10 air conditioning systems were replaced with SEER-12 air conditioning systems in order to improve the energy efficiency of these systems.

Figure 7.36 shows the annual energy use of the improved model entitled Strategy 7 as compared to that of the base-case simulation. The BEPS output of the improved model Strategy 7, as compared to the base-case simulation is shown in Table 7.18. From Figure 7.36 and Table 7.18, it can be seen that the energy used for space cooling decreased by 12.6 percent. This resulted in a decrease of total energy consumption by 3.5 percent, or 187 kWh per year. No significant change occurred in the space temperature profiles.

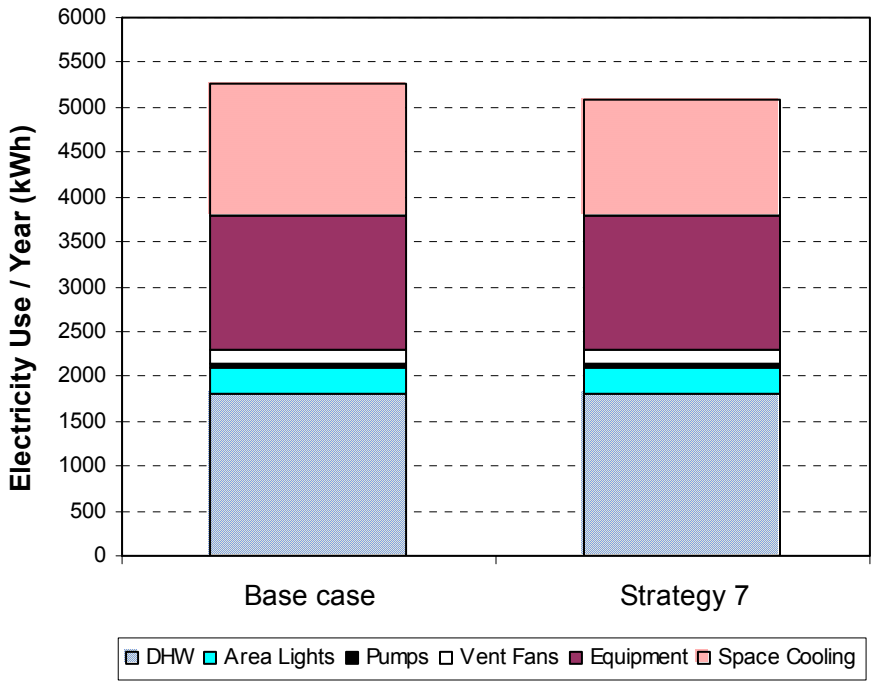


Figure 7.36 *Comparison of the Annual Energy Use of the Base Case and Building Improvement Strategy 7.*

TABLE 7.18

Building Energy Performance Summary: Base Case vs. Strategy 7

Category of Use	Annual Site Energy Consumptions			
	Base case	Improved Model	Energy Saved	
	kWh	kWh	kWh	(%)
Area Lights	280	280	0	0.0
Equipment	1497	1497	0	0.0
Space Cooling	1480	1293	187	12.6
Pumps	46	46	0	0.0
Vent Fans	165	165	0	0.0
Domestic Hot Water	1807	1807	0	0.0
Total	**5275**	**5088**	**187**	**3.5**

7.3.8 Strategy 8: Electronic Ballasts

This strategy aimed to improve the building's lighting system. The base-case house's lighting systems used fluorescent lamps as its lighting source. Fluorescent lamps are very energy efficient. However, the fluorescent lamps in the case-study house were connected to magnetic ballasts. These magnetic ballasts are less energy efficient than electronic ballasts. Replacing the magnetic ballasts with electronic ballasts improves the overall efficiency of the lighting system. Thus, the energy use for lighting was reduced. Besides saving energy through the replacement of the electronic ballasts, electronic ballasts are often less noisy when operating (Stein, B. and J.S. Reynolds, 1992).

Figure 7.37 shows the annual energy use of Strategy 8 as compared to that of the base-case simulation. The BEPS output of Strategy 8 as compared to the base case is shown in Table 7.19. From Figure 7.37 and Table 7.19, it can be seen that the energy used for the lighting system decreased by 13.2 percent. This resulted in a decrease of total energy consumption by 0.8 percent, or 40 kWh per year.

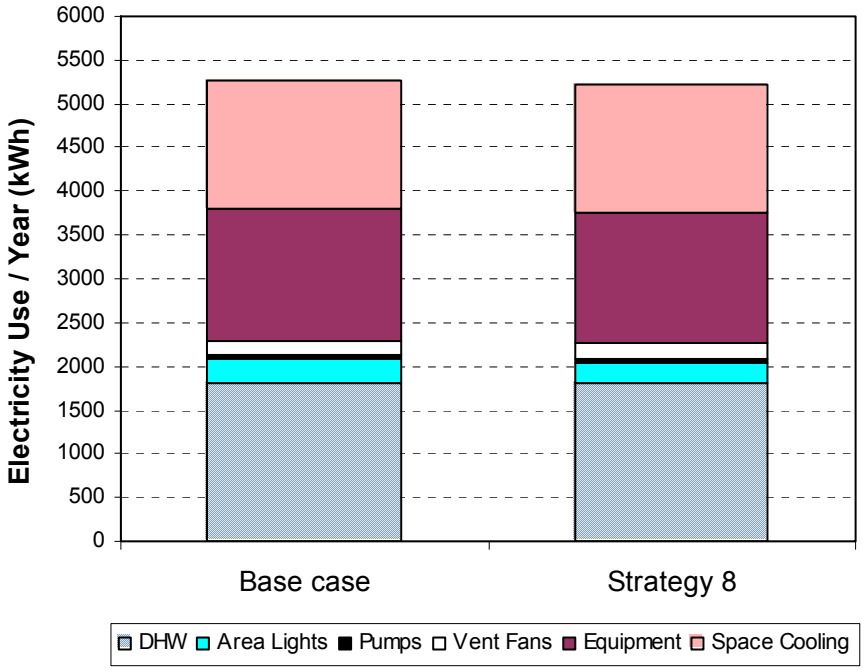


Figure 7.37 *Comparison of the Annual Energy Use of the Base Case and Building Improvement Strategy 8.*

TABLE 7.19

Building Energy Performance Summary: Base Case vs. Strategy 8

Category of Use	Annual Site Energy Consumptions			
	Base case	Improved Model	Energy Saved	
	kWh	kWh	kWh	(%)
Area Lights	280	243	37	13.2
Equipment	1497	1497	0	0.0
Space Cooling	1480	1477	3	0.2
Pumps	46	46	0	0.0
Vent Fans	165	165	0	0.0
Domestic Hot Water	1807	1807	0	0.0
Total	**5275**	**5235**	**40**	**0.8**

7.3.9 Strategy 9: High Efficiency Refrigerators

This energy efficiency strategy replaced the existing refrigerators with energy efficient models. There were two refrigerators in the case-study house. The first one, in the kitchen, had a volume of 14 ft^3 and a rated annual energy use of 657 kWh per year. The second one, in the second floor hall, had a volume of 6.5 ft^3 and a rated annual energy use of 427 kWh per year. The first refrigerator was replaced with a 14.54 ft^3 refrigerator that had a rated annual energy use of 372 kWh per year. The second refrigerator was replaced with a 4.9 ft^3 refrigerator that had a rated annual energy use of 316 kWh per year. The second new refrigerator's size was smaller than that of the existing one because it was reported by the occupants that the refrigerator was only used to refrigerate a few small items such as medicine and milk.

Figure 7.38 shows the annual energy use of the improved model entitled Strategy 9 as compared to that of the base case. The BEPS of the improved model Strategy 9 as compared to the base case is shown in Table 7.20. From Figure 7.38 and Table 7.20, it can be seen that the

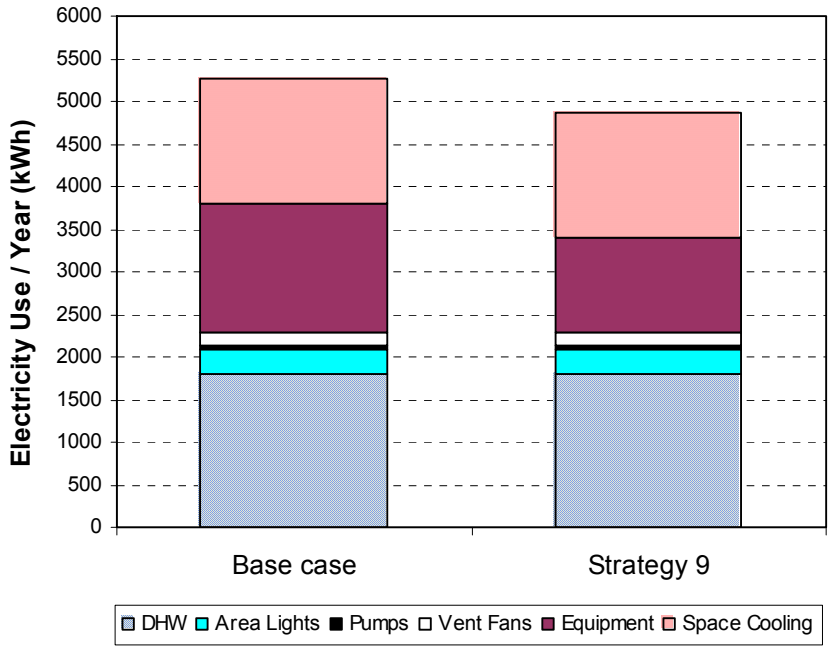


Figure 7.38 *Comparison of the Annual Energy Use of the Base Case and Building Improvement Strategy 9.*

energy used for the equipment decreased by 26.2 percent. This resulted in a decrease of total energy consumption by 7.7 percent, or 404 kWh per year.

TABLE 7.20

Building Energy Performance Summary: Base Case vs. Strategy 9

Category of Use	Annual Site Energy Consumptions			
	Base case kWh	Improved Model kWh	Energy Saved kWh	Energy Saved (%)
Area Lights	280	280	0	0.0
Equipment	1497	1105	392	26.2
Space Cooling	1480	1469	11	0.7
Pumps	46	46	0	0.0
Vent Fans	165	164	1	0.6
Domestic Hot Water	1807	1807	0	0.0
Total	**5275**	**4871**	**404**	**7.7**

The reduction of energy use by the new refrigerators resulted in a decrease in the sensible loads from the heat that the refrigerators contributed to the living-dining room and the second floor hall. In Figure 7.39, the upper left graph shows the results of the base-case equipment's sensible load in the living-dining room area, where the first refrigerator was situated as compared to that of Strategy 9. The graph shows the sensible load that the space gained from the equipment (appliances) including a television set, microwave oven, and refrigerator. The graph shows that after the new refrigerator was installed, the equipment's sensible load in the living-dining room dropped significantly. At the peak equipment load, which occurred at 6:00 p.m., the load was reduced by approximately 17 percent (from 409 Btu/hr to 341 Btu/hr). In Figure 7.39, the reduction in the living-dining room's electricity load in Btu/hr is presented in the lower left graph. The electricity load profile shown in the graph is the total electricity load of the living-dining room, which includes the electricity used by lighting and equipment. The graph shows that the total electricity used in this space was reduced by the installation of the new refrigerator. The electricity only consumed by the refrigerator from midnight to 6:00 a.m. can also be seen in the graph. During this period, all fluorescent lamps were switched off, and the refrigerator was the only appliance operating. The

refrigerator's energy use was reduced by approximately 43 percent [from 256 Btu/hr (81.47 Watts) to 145 Btu/hr (46 Watts)]. The reduction of heat from the refrigerator caused the space temperatures of the living-dining room to slightly decrease by 0.2 ºF (annual average) as shown in 7.40.

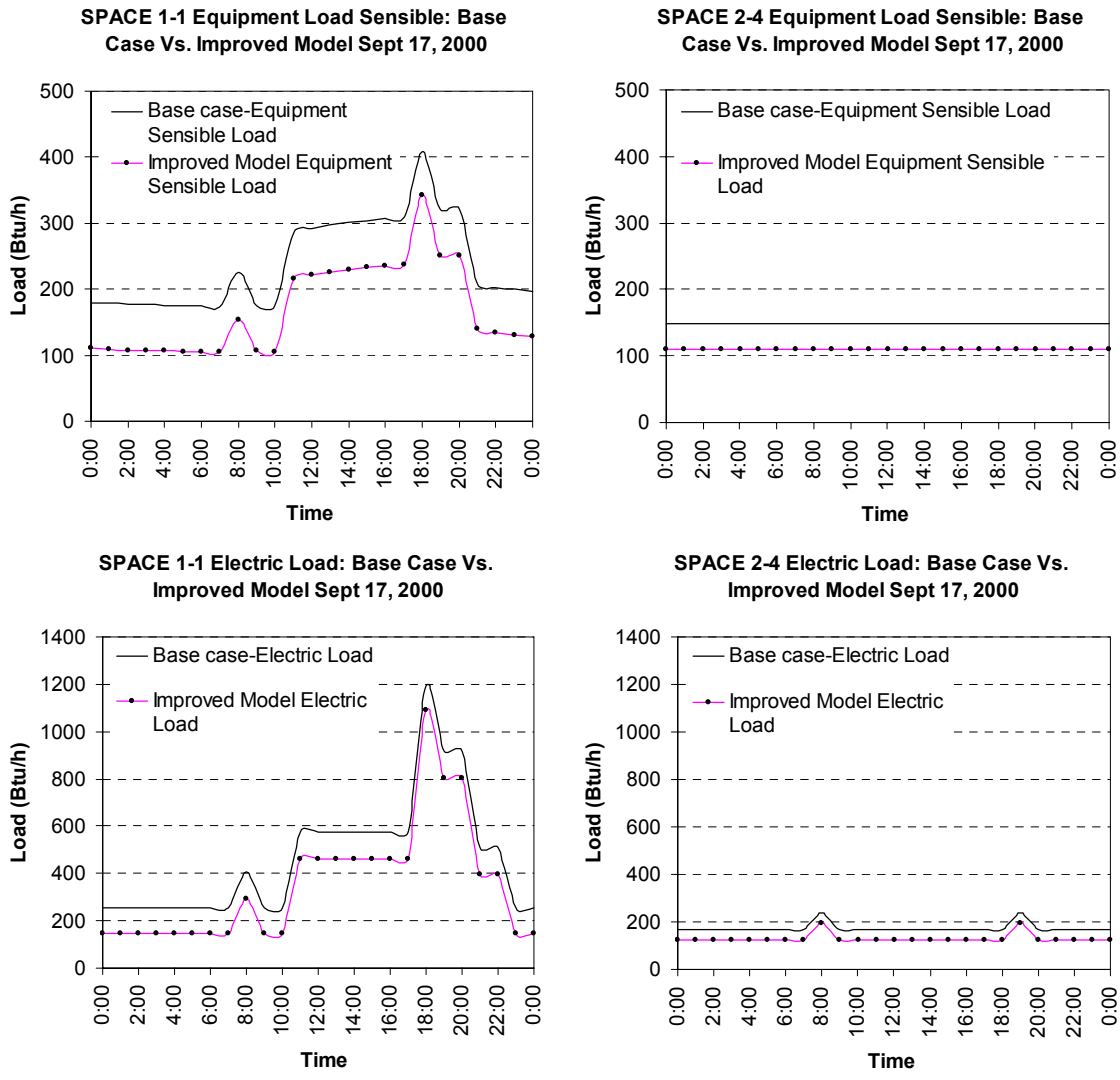


Figure 7.39 *Comparison Between the Base Case and Strategy 9:Equipment Loads and the Electricity Load of Space 1-1 and 2-4.*

The results of the replacement of the second floor's refrigerator were similar to the results of the first refrigerator's replacement. The upper right graph in Figure 7.39 shows the results of the base-case equipment's sensible loads in the second floor hall where the second refrigerator was situated as compared to that of Strategy 9. The refrigerator was the only equipment in this space, so the graph represents the refrigerator's sensible load. As shown in the graph, the space's sensible load dropped by approximately 26 percent (from 149 Btu/hr or 43.7 Watts to 111 Btu/hr or 32.5 Watts). In Figure 7.38, in the lower right graph, the reduction in the second floor hall's electricity load in Btu/hr was also presented. Besides the refrigerator, the electricity load in this space also included the load from the lighting system. The "bumps" in this graph were the electricity load caused by the assumed operation of a fluorescent lamp in the bathroom (the hall and the bathroom were assigned as one space/zone in the DOE-2). The graph shows that the new refrigerator reduced the space's electric load by approximately 26 percent (from 166 Btu/hr or 48.7 Watts to 123 Btu/hr or 36 Watts). The reduction of heat from the refrigerator caused the second floor's hall temperatures to slightly decrease by 0.3 ºF (annual average) as shown in Figure 7.41.

In summary, high energy efficient refrigerators not only reduced the building's energy consumption, they also improved space temperatures by contributing less heat to the spaces.

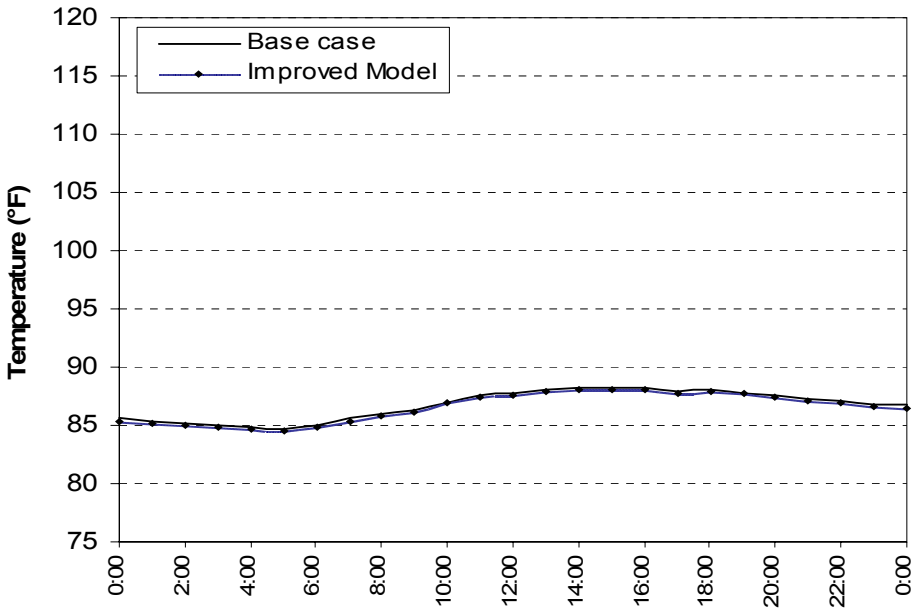


Figure 7.40 *Comparison between Base Case and Strategy 9 Living-Dining Temperatures.*

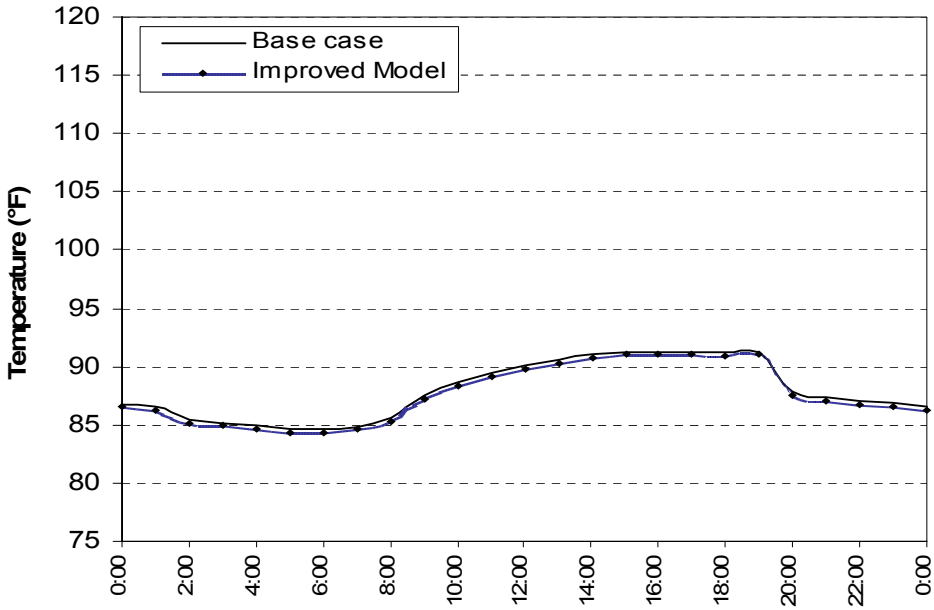


Figure 7.41 *Comparison between Base Case and Strategy 9 2nd Floor Hall Temperatures.*

7.3.10 Strategy 10: Renewable Energy Technology 1 (Hybrid PV-T^2 Collector System)

This section presents the results from the analysis of supplemental thermal and electrical energy from the hybrid-PV-T^2 collector system. The objective of this analysis was to supply all domestic hot water (DHW) needs by the hybrid-PV-T^2 collector system. Thus, the size of the hybrid PV-T^2 array was first analyzed by using the F-Chart program to determine the required thermal energy to supply the DHW load. Then, the electrical energy produced by the hybrid-PV-T^2 collector system (with the same array size) was analyzed by the PV-F Chart program. The results of thermal and electrical energy produced by the hybrid-PV-T^2 collector system are presented below. The input parameters and the output from F-Chart and PV-F chart programs are presented and discussed in the Appendix F.

From the analysis of thermal energy produced by the hybrid PV-T^2 collectors, the required collector area to meet all of the DHW monthly loads was 294 ft^2. Of this collector area, 170 ft^2 (the maximum available area on the south side roof) and 124 ft^2 of the collector were installed on the south and west sides of the roof, respectively. Figure 7.42 shows the monthly results of both south and west sides of the hybrid PV-T^2 collector arrays. In Figure 7.42, it can be seen that the south facing collectors could not supply all the DHW monthly demands. The highest percentage of the monthly DHW supply to the demand is in March (87 percent), and the lowest are in June (63 percent) and August (64 percent), respectively. Thus, June and August were the key months to determine the required area of the collectors. The west side collectors provided more thermal energy to fulfill the DHW load as shown in Figure 7.42. The area of the west-side collectors was increased until all of the monthly DHW loads were fully supplied.

Figure 7.43 shows the fraction of the energy supply by the collector to the DHW load (F) versus collector area (combined south and west side roof). In the Figure 7.43, only the key months (July and October) and the annual average of the fraction of solar supplied were plotted on the graph (i.e., F factor). As shown in the figure, October required the largest area of collectors (294 ft^2). Therefore, the required hybrid PV-T^2 collector area was determined to be 294 ft^2.

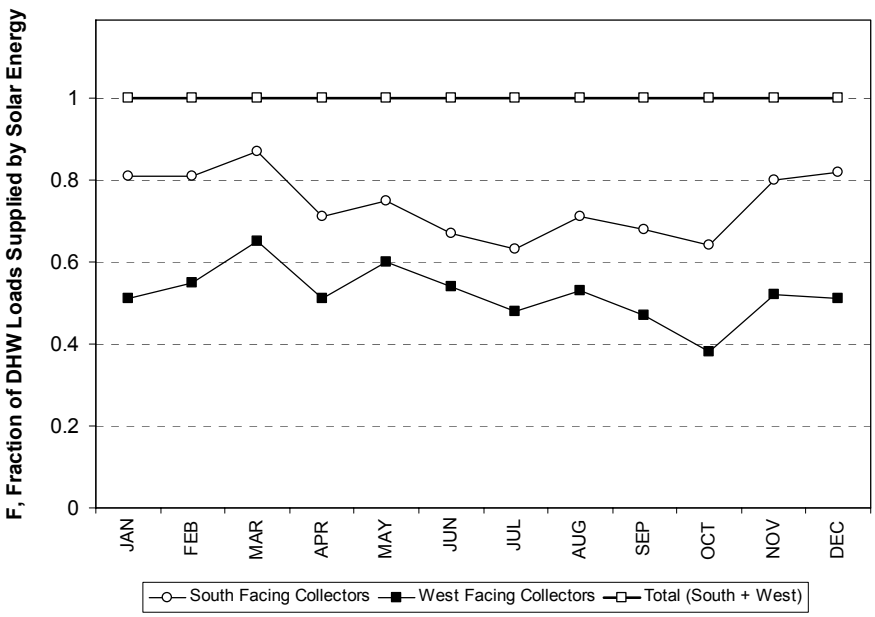


Figure 7.42 *Fraction of Supplemental Solar DHW to the DHW Loads (F) of the South and West Facing Hybrid PV-T² Arrays.*

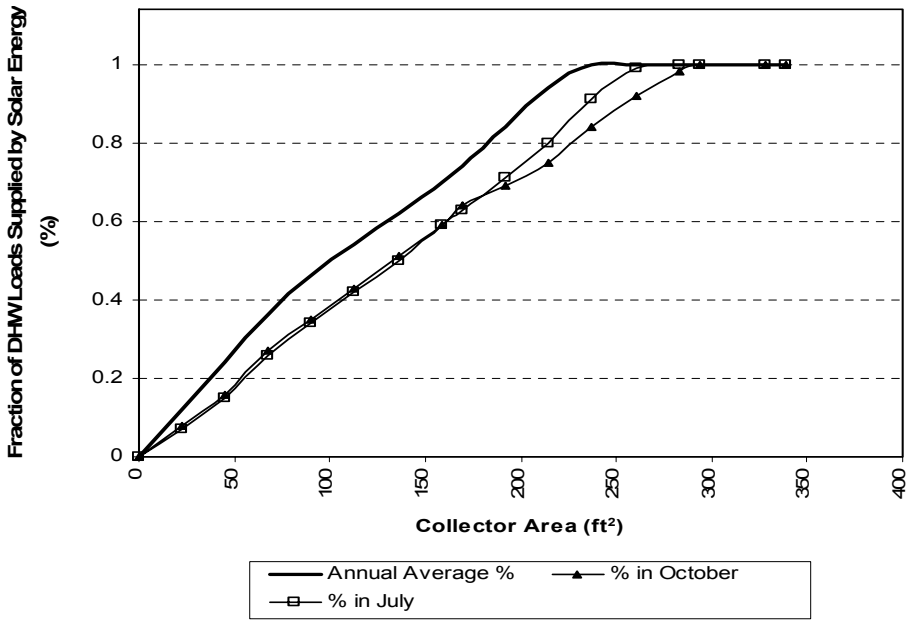


Figure 7.43 *Fraction of Supplemental Solar DHW to the DHW Loads (F) of the South and West Facing Hybrid PV-T² Arrays Versus Collector Area. July and October were key months to determine the hybrid PV-T² collector area.*

Figure 7.44 shows the annual energy use of the improved model as compared to that of the base case. In this analysis the monthly DHW use was reduced by the amount provided by the collector. The BEPS output of the improved model as compared with the base case is shown in Table 7.21. From Figure 7.44 and Table 7.21, energy used for DHW was reduced by 100 percent, since every month's DHW demands were met. For the supplemental electrical energy, the energy used for lighting was reduced by 14.2 percent (daytime lighting load accounts for 14 percent of the total lighting load). The energy use for equipment, pump, air conditioning systems, and ventilation fans were reduced by 25.1, 100, 0.8 and 0.6 percent. The reductions in the energy used for air conditioning systems and ventilation fans were caused by the shading of the hybrid-PV-T^2 arrays. From all the results, the total energy consumption was reduced by 43.3 percent, or 2282 kWh per year.

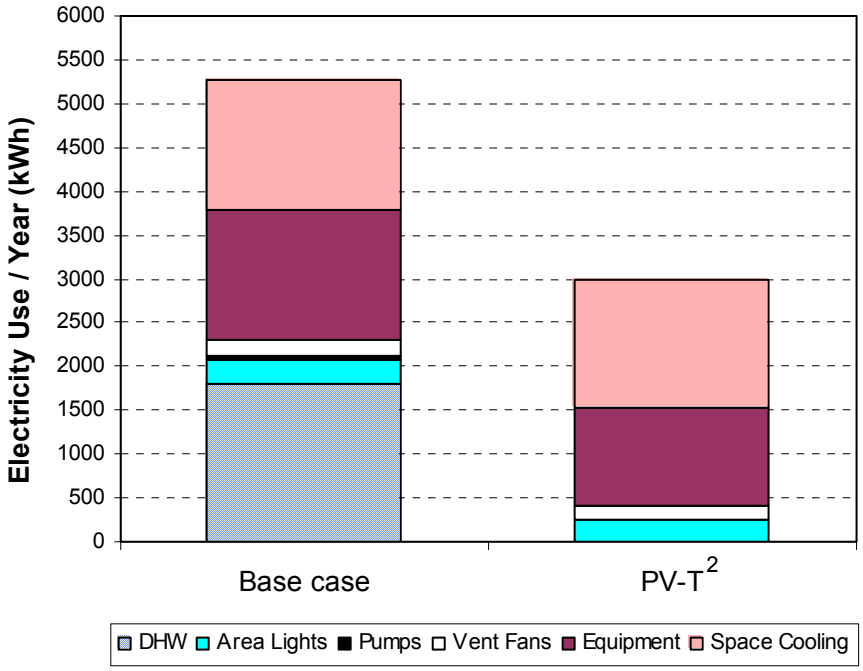


Figure 7.44 *Comparison between Annual Energy Use of Base Case and Building Improved with a Hybrid PV-T^2 Collector System.*

TABLE 7.21

Building Energy Performance Summary: Base Case vs. Building Improved by a Hybrid PV-T^2 Collector System

Category of Use	Annual Site Energy Consumptions			
	Base case	Improved Model	Energy Saved	
	kWh	kWh	kWh	(%)
Area Lights	280	240	40	14.3
Equipment	1497	1121	376	25.1
Space Cooling	1480	1468	12	0.8
Pumps	46	0	46	100.0
Vent Fans	165	164	1	0.6
Domestic Hot Water	1807	0	1807	100.0
Total	**5275**	**2993**	**2282**	43.3

7.3.11 Strategy 11: Renewable Energy Technology 2 (Photovoltaic System)

This section presents the results from the analysis of supplemental electrical energy from a PV system. PV modules were installed on all available area of the roof (1053 ft^2). The results of the analysis of the supplemental electric energy are presented as a plot of the electric demand versus collector area in Figure 7.45. In the figure, it can be seen that the maximum electricity supplied by the PV system was only 0.22 percent of the total electric demand. This was due to most of electricity loads occurring in the nighttime when there was no electrical supply from the PV, and the fact that the system was configured without battery.

Figure 7.46 shows the annual energy use of the improved model as compared to that of the base-case simulation. The BEPS output of the improved model as compared with the base case is shown in Table 7.22. In this table the PV electric output was deducted against the equipment load. From Figure 7.46 and Table 7.22, energy use for area lighting, equipment, space cooling, pump, and ventilation fans were reduced by 14.2, 72.8, 3.3, 100, and 3.0 percent, respectively. These reductions of space cooling and ventilation fans are more than that of the Renewable Energy Technology 1 (hybrid PV-T system), since there was more roof area that was covered by the PV arrays (In the analysis using DOE-2, the PV arrays were simulated as

shading on the roof). From all results, the total energy consumption was reduced by 23.3 percent, or 1229 kWh per year.

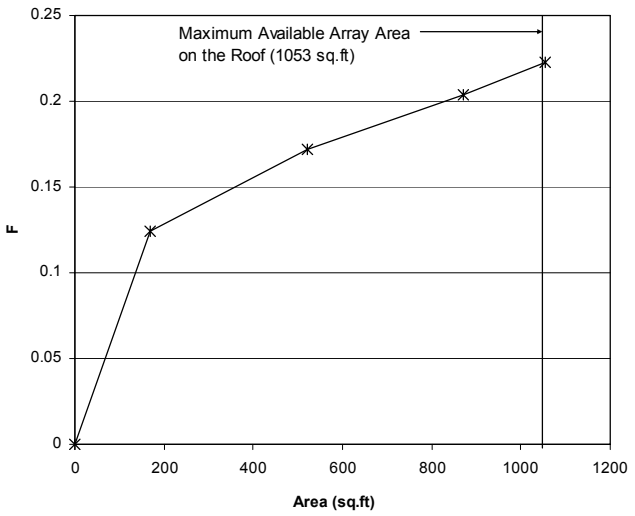


Figure 7.45 *Fraction of the Supplemental Electricity to the Electricity Load (F-factor) of the PV Arrays (Combined South, West, East, and North PV arrays) Versus Collector Area.*

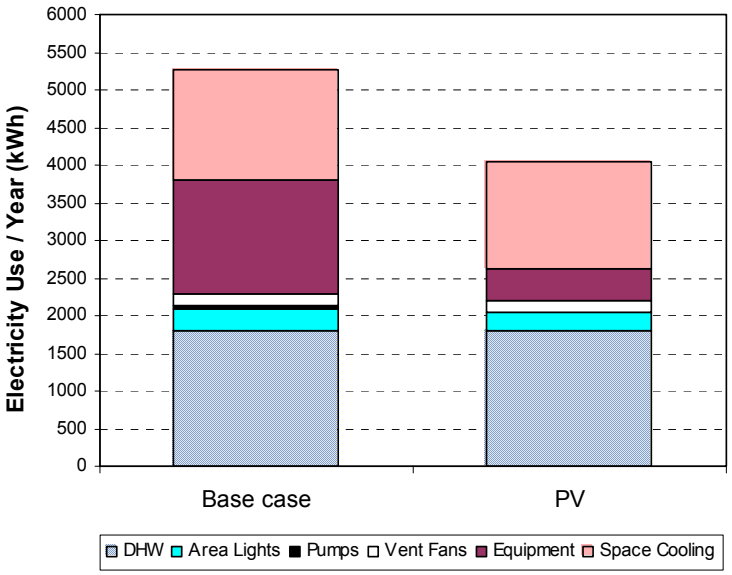


Figure 7.46 *Comparison Between Annual Energy Use of Base Case and Building Improved with a Photovoltaic System.*

TABLE 7.22

Building Energy Performance Summary: Base Case vs. Building Improved by PV System

Category of Use	Annual Site Energy Consumptions			
	Base case	Improved Model	Energy Saved	
	kWh	kWh	kWh	(%)
Area Lights	280	240	40	14.2
Equipment	1497	408	1089	72.8
Space Cooling	1480	1431	49	3.3
Pumps	46	0	46	100.0
Vent Fans	165	160	5	3.0
Domestic Hot Water	1807	1807	0	0.0
Total	**5275**	**4046**	**1229**	**23.3**

7.3.12 Strategy 12: Renewable Energy Technology 3 (Hybrid PV-T^2 Collector System and Photovoltaic System)

This section presents the combination of results from the analysis of supplemental thermal and electrical energy from the hybrid-PV-T^2 collector system (from Section 7.3.10: Renewable Energy Technology 1) and the results from the analysis of a photovoltaic system. The results of supplemental electrical energy produced by the photovoltaic system were not obtained from Section 7.3.11, since the available installation area of the PV arrays was changed. The PV array shared the roof area with the hybrid PV-T^2 array. Thus, the electrical energy produced by the PV system was recalculated.

Figure 7.47 shows the annual energy use of the improved model as compared to that of the base-case simulation. The BEPS output of the improved model as compared with the base case is shown in Table 7.23. From Figure 7.47 and Table 7.23, energy use for area lighting, equipment, space cooling, pump, and ventilation fans were reduced by 14.2, 50.1, 4.2, 100, and 3.6 percent. The energy used for DHW was reduced by 100 percent, since the hybrid-PV-T^2 system was able to provide all DHW demands. From all results, the total energy consumption was reduced by 51.4 percent, or 2,710 kWh per year.

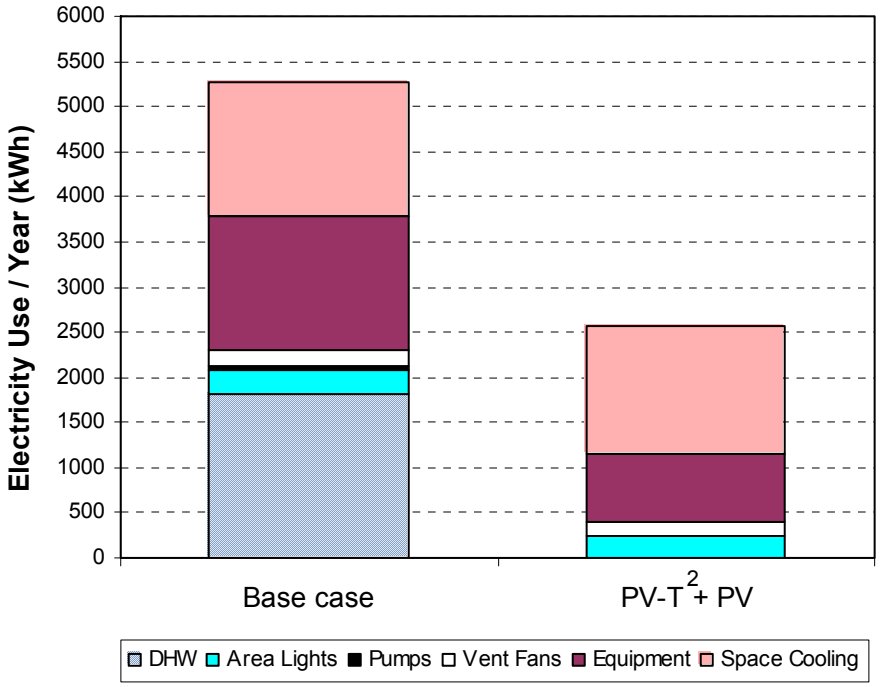


Figure 7.47 *Comparison between Annual Energy Use of Base Case and Building Improved with a Hybrid PV-T^2 Collector System and a Photovoltaic System.*

TABLE 7.23

Building Energy Performance Summary: Base Case vs. Building Improved by a Hybrid PV-T^2 Collector System and a Photovoltaic System

Category of Use	Annual Site Energy Consumptions			
	Base case	Improved Model	Energy Saved	
	kWh	kWh	kWh	(%)
Area Lights	280	240	40	14.2
Equipment	1497	748	749	50.1
Space Cooling	1480	1418	62	4.2
Pumps	46	0	46	100.0
Vent Fans	165	159	6	3.6
Domestic Hot Water	1807	0	1807	100.0
Total	**5275**	**2565**	**2710**	**51.4**

7.3.13 Strategy 13: Renewable Energy Technology 4 (Flat-Plate Solar Collector)

From the results of the analysis of supplemental thermal energy in Sections 7.3.10 and 7.3.12, it was found that it required a lot of area of the hybrid-PV-T^2 collector to supply all domestic hot water (DHW) needs. This is because of the low thermal efficiency of the hybrid-PV-T^2 collector. Thus, a solar collector system (double glazing flat-plate collector system), which has relatively high thermal efficiency and is a popular type of solar collector, was selected to include in the analysis of supplemental thermal energy for DHW by the F-Chart program. This section presents the results from the analysis of supplemental thermal energy from a double glazing flat-plate collector system. The technical data of this collector was obtained from Klein and Beckman (1985). The input parameters and the output from the F-Chart program are presented and discussed in the Appendix F.

Figure 7.48 shows the fraction of the energy supply by the collector to the DHW load (F) versus collector area (combined south and west side roof). In the Figure 7.48, only the key months (July and October) and the annual average of the fraction of solar supplied "F" were plotted on the graph. As shown in the figure, October required the largest area of collector

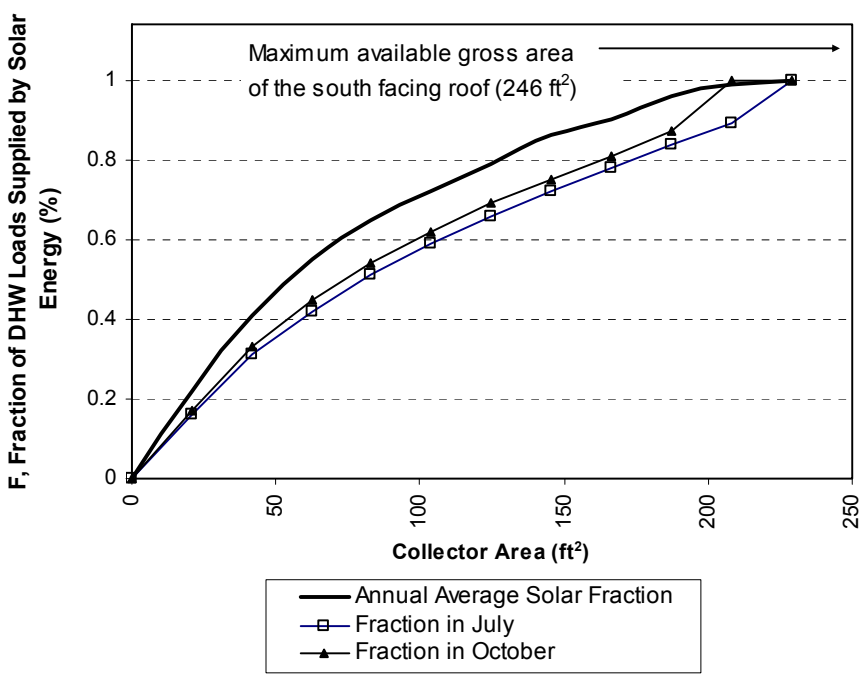


Figure 7.48 *Fraction of the Supplemental Solar DHW to the DHW Loads (F) of the South Facing Flat-Plate Solar Collector Arrays Versus Collector Area. July and October were key months to determine the collector area.*

(approximately 230 ft^2). Therefore, the required collector area was 230 ft^2. From this result, the required collector area to supply all DHW needs by the flat plate solar collector is about 22 percent less than the hybrid-PV-T^2 collector which required 290 ft^2. This confirms that the flat plate solar collector actually has higher thermal efficiency than the hybrid-PV-T^2 collector.

Figure 7.49 shows the annual energy use of the improved model as compared to that of the base-case simulation. The BEPS output of the improved model as compared with the base case is shown in Table 7.24. From Figure 7.49 and Table 7.24, there were no changes in energy use for area lighting, equipment, space cooling, pump, and ventilation fans. The energy used for DHW was reduced by 100 percent, since the flat plate solar collector system was able to provide all DHW demands. However, there was an increase of the energy use by the pump that was a part of the solar collector system. The pump for the solar collector system (100 W) was estimated to operate 12 hours per day for 365 days, which consumed electricity about 438 kWh per year. From all results, the total energy consumption was reduced by 26.7 percent, or 1,490 kWh per year.

TABLE 7.24

Building Energy Performance Summary: Base Case vs. Building Improved by a Flat Plate Solar Collector System

Category of Use	Annual Site Energy Consumptions			
	Base case	Improved Model	Energy Saved	
	kWh	kWh	kWh	(%)
Area Lights	280	240	40	14.3
Equipment	1497	1497	0	0.0
Space Cooling	1480	1480	0	0.0
Pumps	46	484	-438	-952.2
Vent Fans	165	165	0	0.0
Domestic Hot Water	1807	0	1807	100.0
Total	**5275**	**3866**	**1409**	**26.7**

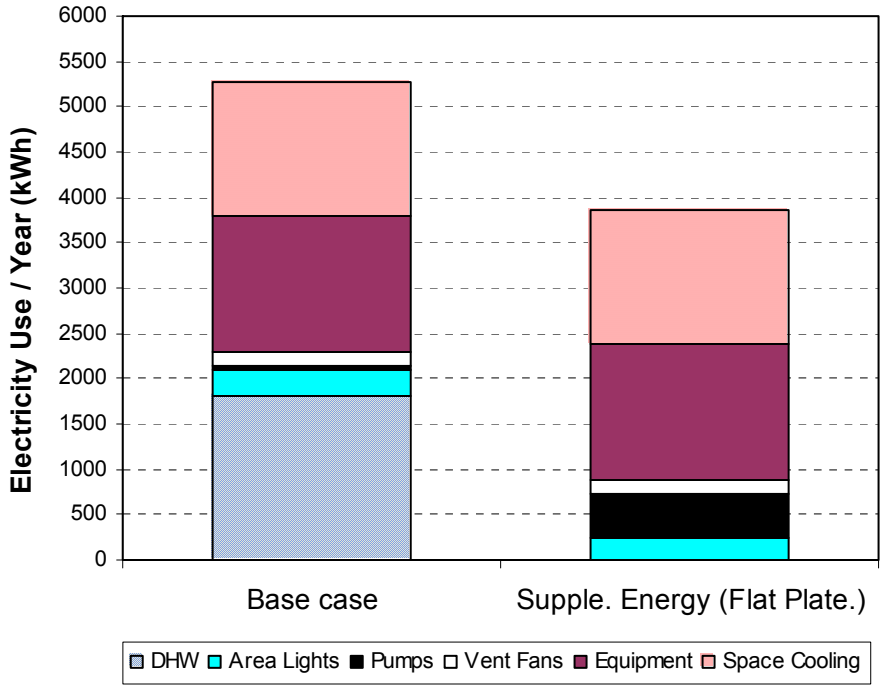


Figure 7.49 *Comparison between Annual Energy Use of Base Case and Building Improved with a Flat Plate Solar Collector System.*

7.3.14 Combination A: Combination of Strategies 2, 3-4, 7, 8, and 9

Combination A is a strategy that combines Strategies 2, 3-4, 7, 8, and 9 together. The second floor ceiling was upgraded from existing R-11 to R-28 fiberglass insulation. The 4-inch brick walls were replaced by the insulated 4-inch light-weight concrete walls (Strategy 3-4). The air conditioning systems (Strategy 7) were replaced by higher energy efficiency air conditioning system (upgraded from SEER-10 to SEER-12). The existing refrigerators (Strategy 9) were replaced with the new refrigerators that consume much less energy. The magnetic ballasts were replaced by more energy efficient electronic ballasts.

Figure 7.50 shows the annual energy use of the improved model entitled Combination A, as compared to that of the base-case simulation. The BEPS output of the Combination A as compared to the base case is shown in Table 7.25. From Figure 7.50 and Table 7.25, it can be seen that the energy used for area lights, equipment, space cooling and ventilation fans decreased by 15.2, 26.2, 42.2 and 37.6 percent, respectively. The pump and DHW energy uses

were not changed. This resulted in a decrease of total energy consumption by 21.2 percent, or 1,121 kWh per year.

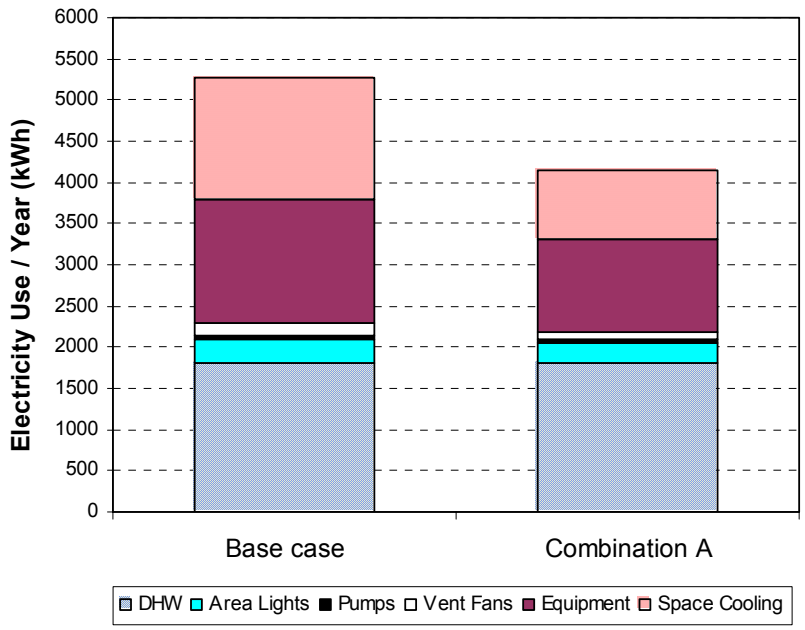


Figure 7.50 *Comparison between Annual Energy Use of Base Case and Combination A.*

TABLE 7.25

Building Energy Performance Summary: Base Case vs. Combination A

Category of Use	Annual Site Energy Consumptions			
	Base case kWh	Improved Model kWh	Energy Saved kWh	Energy Saved (%)
Area Lights	280	238	42.5	15.2
Equipment	1497	1105	392	26.2
Space Cooling	1480	856	624	42.2
Pumps	46	46	0	0.0
Vent Fans	165	103	62	37.6
Domestic Hot Water	1807	1807	0	0.0
Total	**5275**	**4154.5**	**1120.5**	**21.2**

Figure 7.51 shows the simulated zone temperatures of the improved combined model as compared to the base-case simulation. It can be seen that, the results of space temperatures were similar to the results from Strategy 3-4. In general, there were temperatures increased in all spaces as compared to the base-case temperatures except there was a slightly decrease in the living room temperatures from 3:00 p.m. to midnight.

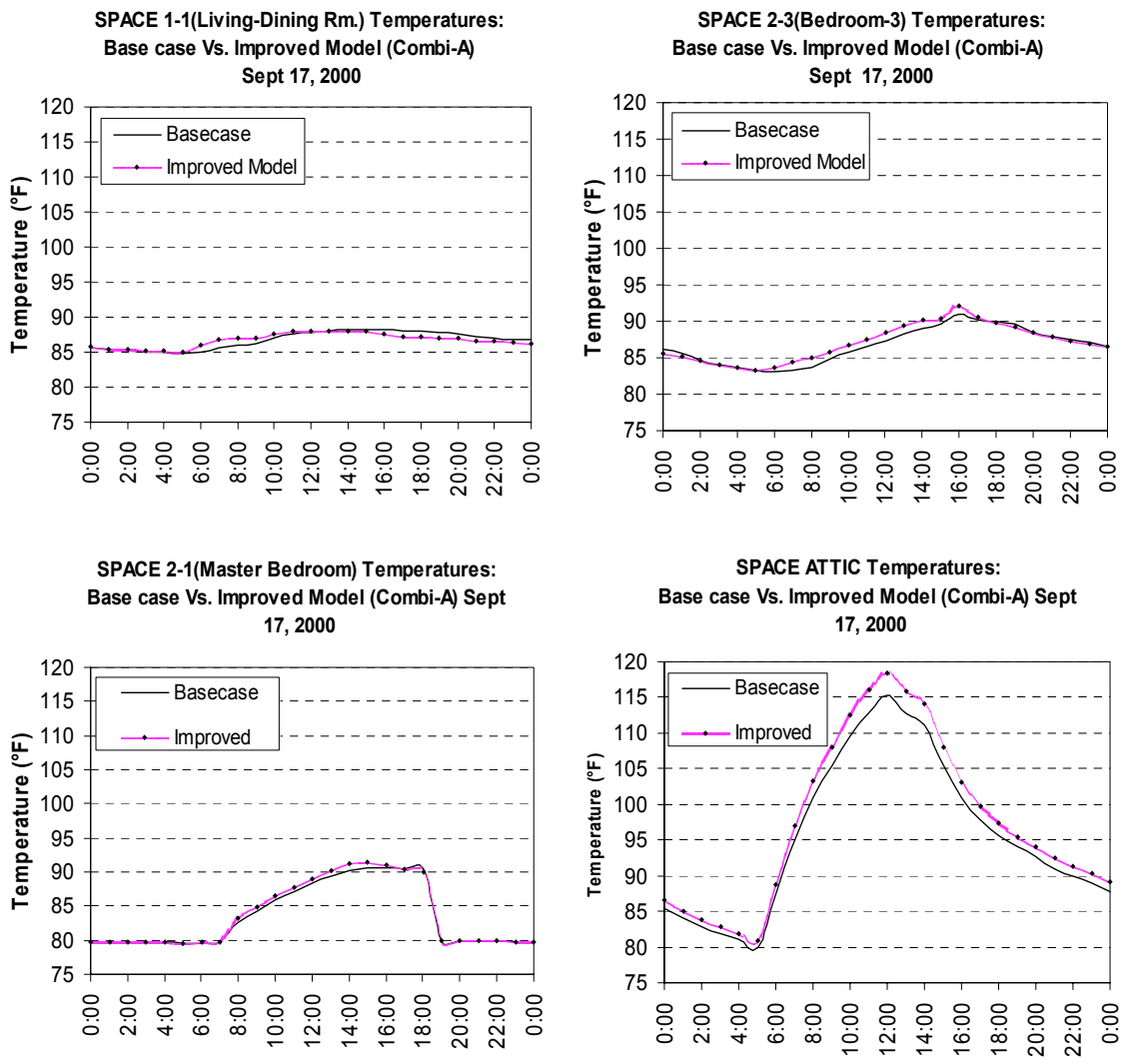


Figure 7.51 *Comparison between Base Case and Combination A Space Temperatures*

7.3.15 Combination B: Combination A Combined with Strategy 4

Combination B combines Combination A with Strategy 4 (Low-E glass). Figure 7.52 shows the annual energy use of the Combination B, as compared to that of the base case. The BEPS of the Combination B as compared to the base case is shown in Table 7.26. From Figure 7.52 and Table 7.26, it can be seen that the energy used for area light, equipment, space cooling and ventilation fans decrease by 15.2, 26.2, 43.1 and 40 percent, respectively. The pump and DHW energy uses were not changed. This resulted in a decrease of total energy consumption by 21.6 percent, or 1,138.5 kWh per year. Thus, this strategy further decreased the building's energy consumption from Combination A which had the annual energy reduction of 1,120.5 kWh, or 21.2 percent.

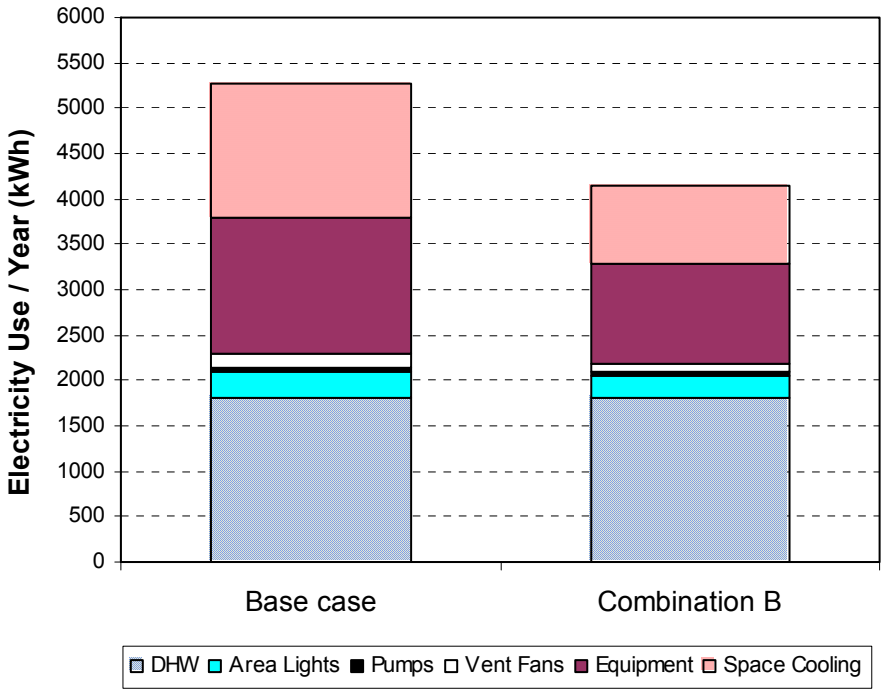


Figure 7.52 *Comparison of Annual Energy Use of Base Case and Combination B.*

TABLE 7.26

Building Energy Performance Summary: Base Case vs. Combination B

Category of Use	Annual Site Energy Consumptions			
	Base case	Improved Model	Energy Saved	
	kWh	kWh	kWh	(%)
Area Lights	280	238	42.5	15.2
Equipment	1497	1105	392	26.2
Space Cooling	1480	842	638	43.1
Pumps	46	46	0	0.0
Vent Fans	165	99	66	40.0
Domestic Hot Water	1807	1807	0	0.0
Total	**5275**	**4136.5**	**1138.5**	**21.6**

While there was only a small improvement of the building energy consumption from Combination A, Combination B's living space temperatures were significantly improved as shown in Figure 7.53. The master bedroom's daytime temperatures decreased from Combination A and were slightly lower than those of the base case. The living room temperatures dramatically dropped throughout the day, especially in the afternoon. However, there was a slight decrease of the bedroom-3 temperature.

From the results of Combination B, there was not only an improvement of the building energy use; the temperatures in living spaces were also improved.

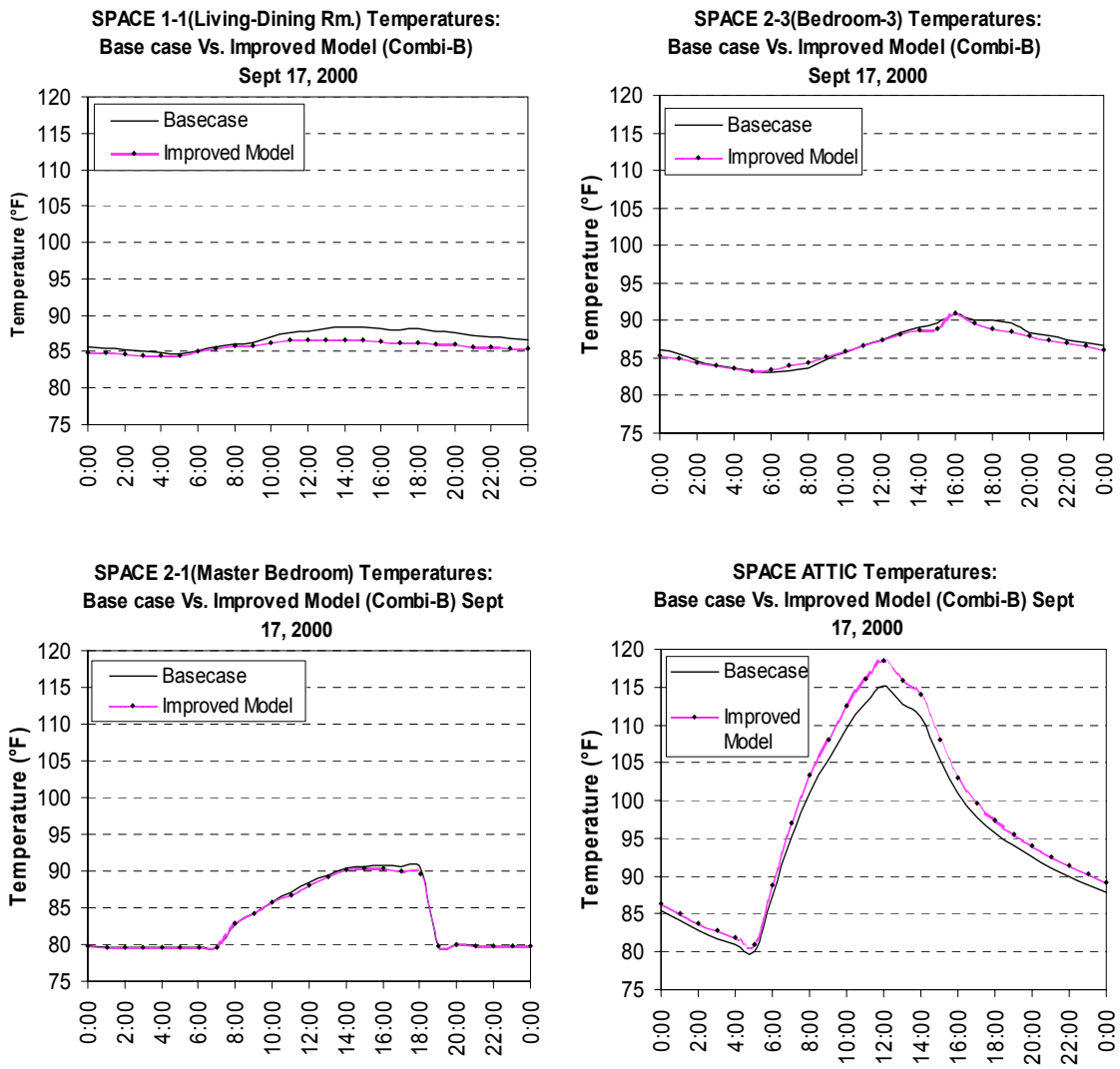


Figure 7.53 *Comparison between Base Case and Combination B Space Temperatures.*

7.3.16 Combination C: Combination A Combined with Strategy 5

Combination C combines Combination A with Strategy 5 (shading devices). Figure 7.54 shows the annual energy use of the Combination C, as compared to that of the base-case simulation. The BEPS output of the Combination C as compared to the base case is shown in Table 7.27. From Figure 7.54 and Table 7.27, it can be seen that the energy used for area light,

equipment, space cooling and ventilation fans decrease by 15.2, 26.2, 42.4 and 38.2 percent, respectively. The pump and DHW energy uses were not changed. This resulted in a decrease of total energy consumption by 21.3 percent, or 1,124.5 kWh per year. Thus, there was no significant reduction in the building's energy consumption as compared to Combination A which had the annual energy reduction of 1,120.5 kWh, or 21.2 percent.

For space temperatures, the temperatures in all spaces were similar to those of Combination A, thus the space temperatures were generally higher than the base case's space temperatures as shown in Figure 7.55.

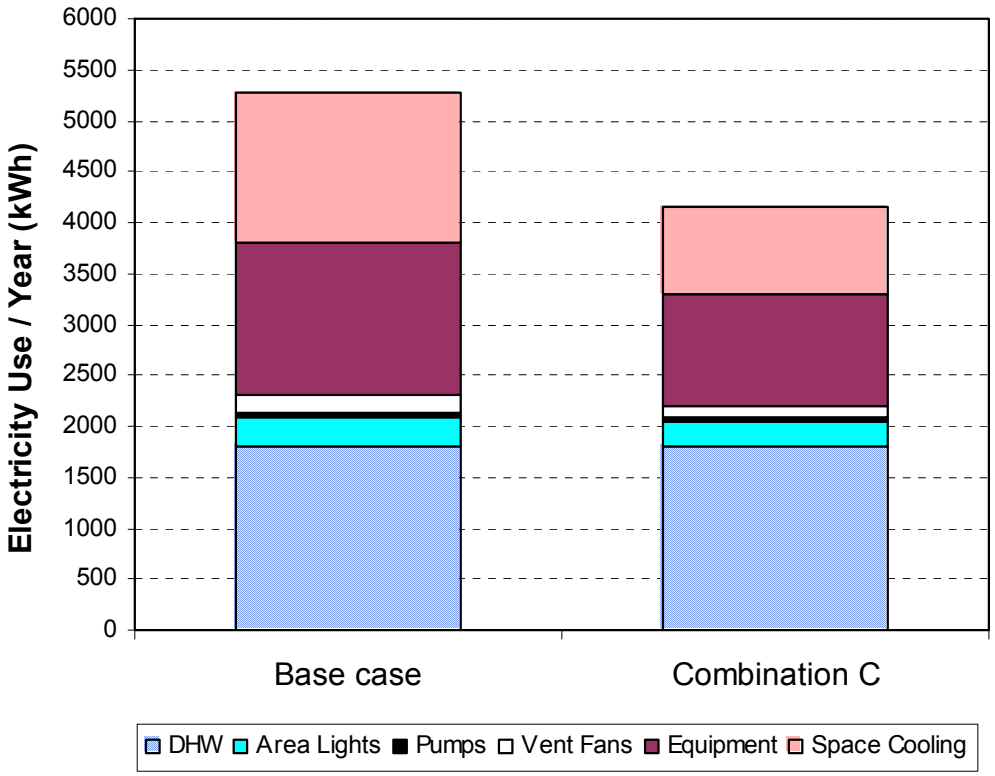


Figure 7.54 *Comparison of Annual Energy Use of Base Case and Combination C.*

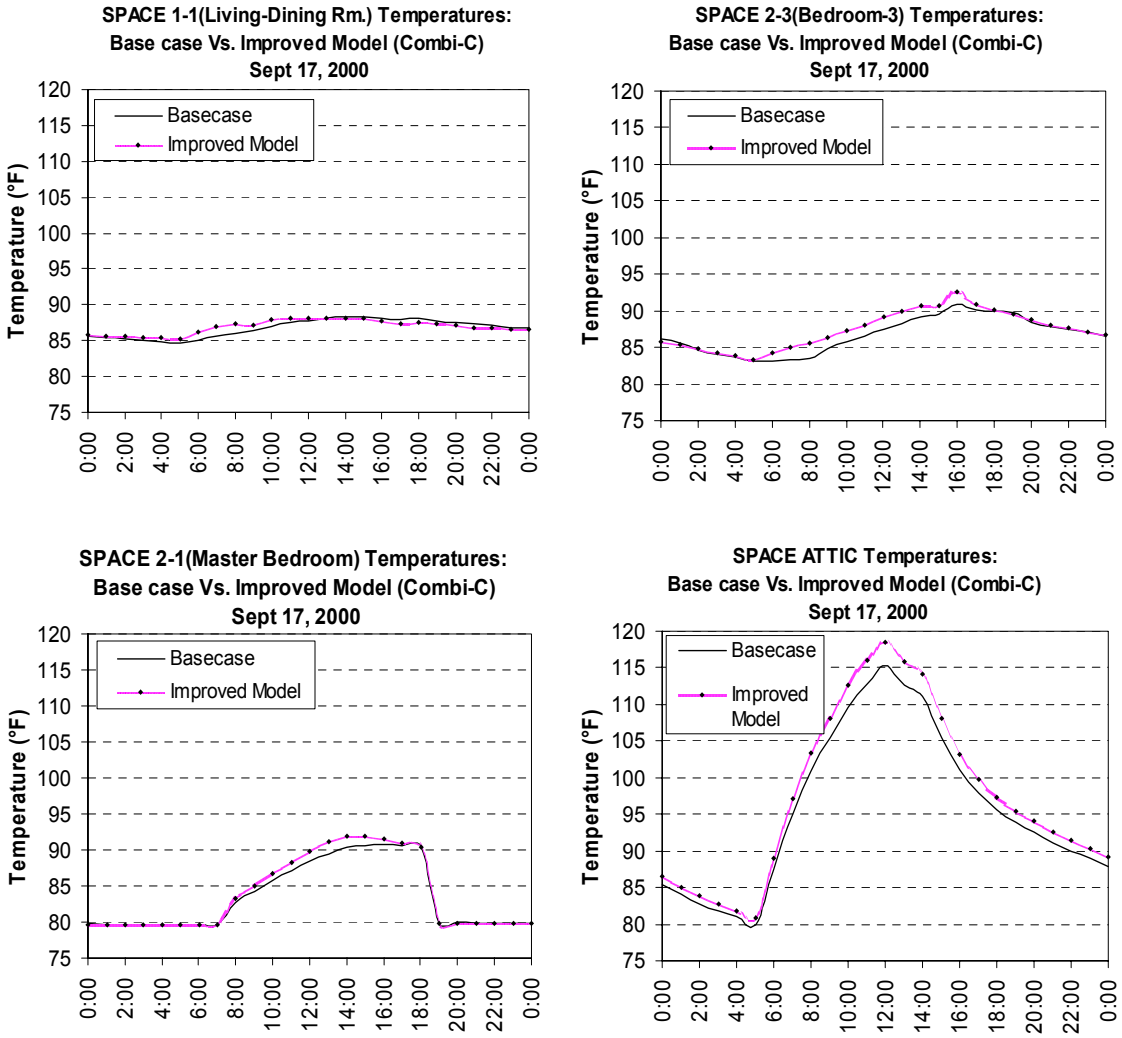


Figure 7.55 *Comparison between Base Case and Combination C Space Temperatures.*

TABLE 7.27

Building Energy Performance Summary: Base Case vs. Combination C

Category of Use	Annual Site Energy Consumptions			
	Base case	Improved Model	Energy Saved	
	kWh	kWh	kWh	(%)
Area Lights	280	238	42.5	15.2
Equipment	1497	1105	392	26.2
Space Cooling	1480	853	627	42.4
Pumps	46	46	0	0.0
Vent Fans	165	102	63	38.2
Domestic Hot Water	1807	1807	0	0.0
Total	**5275**	**4150.5**	**1124.5**	**21.3**

7.3.17 Combination D: Combination A Combined with Strategy 4 and 5

Combination D combines Combination A with Strategies 4 and 5 (Low-E and shading devices, respectively). Figure 7.55 shows the annual energy use of the Combination D, as compared to that of the base case. The BEPS of the Combination D as compared to the base case is shown in Table 7.28. From Figure 7.56 and Table 7.28, it can be seen that the energy used for area light, equipment, space cooling and ventilation fans decrease by 15.2, 26.2, 43.4 and 40.6 percent, respectively. The pump and DHW energy use were not changed. This resulted in a decrease of total energy consumption by 21.7 percent, or 1,143.5 kWh per year. Thus, there was no significant reduction in the building's energy consumption as compared to Combination A, which had the annual energy reduction of 1,120.5 kWh, or 21.2 percent.

For space temperatures, the temperatures in all spaces were similar to those of Combination B, thus the space temperatures decreased from the base-case space temperatures as shown in Figure 7.57. Thus, this shows that, with the presence of low-e windows, the shading devices did not effectively further improve the space temperatures.

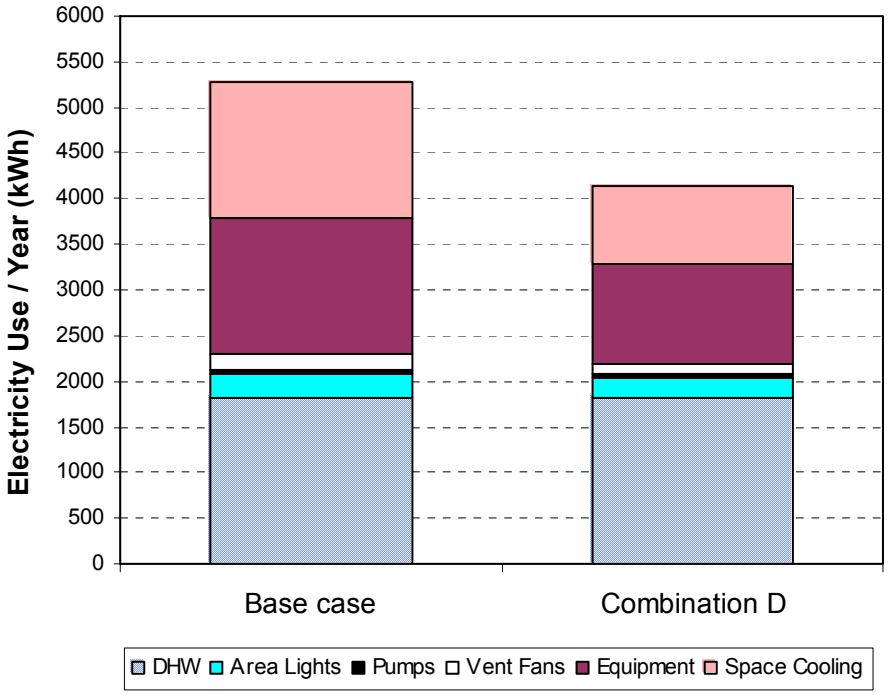


Figure 7.56 *Comparison of Annual Energy Use of Base Case and Combination D.*

TABLE 7.28

Building Energy Performance Summary: Base Case vs. Combination D

Category of Use	Annual Site Energy Consumptions			
	Base case	Improved Model	Energy Saved	
	kWh	kWh	kWh	(%)
Area Lights	280	238	42.5	15.2
Equipment	1497	1105	392	26.2
Space Cooling	1480	838	642	43.4
Pumps	46	46	0	0.0
Vent Fans	165	98	67	40.6
Domestic Hot Water	1807	1807	0	0.0
Total	**5275**	**4131.5**	**1143.5**	**21.7**

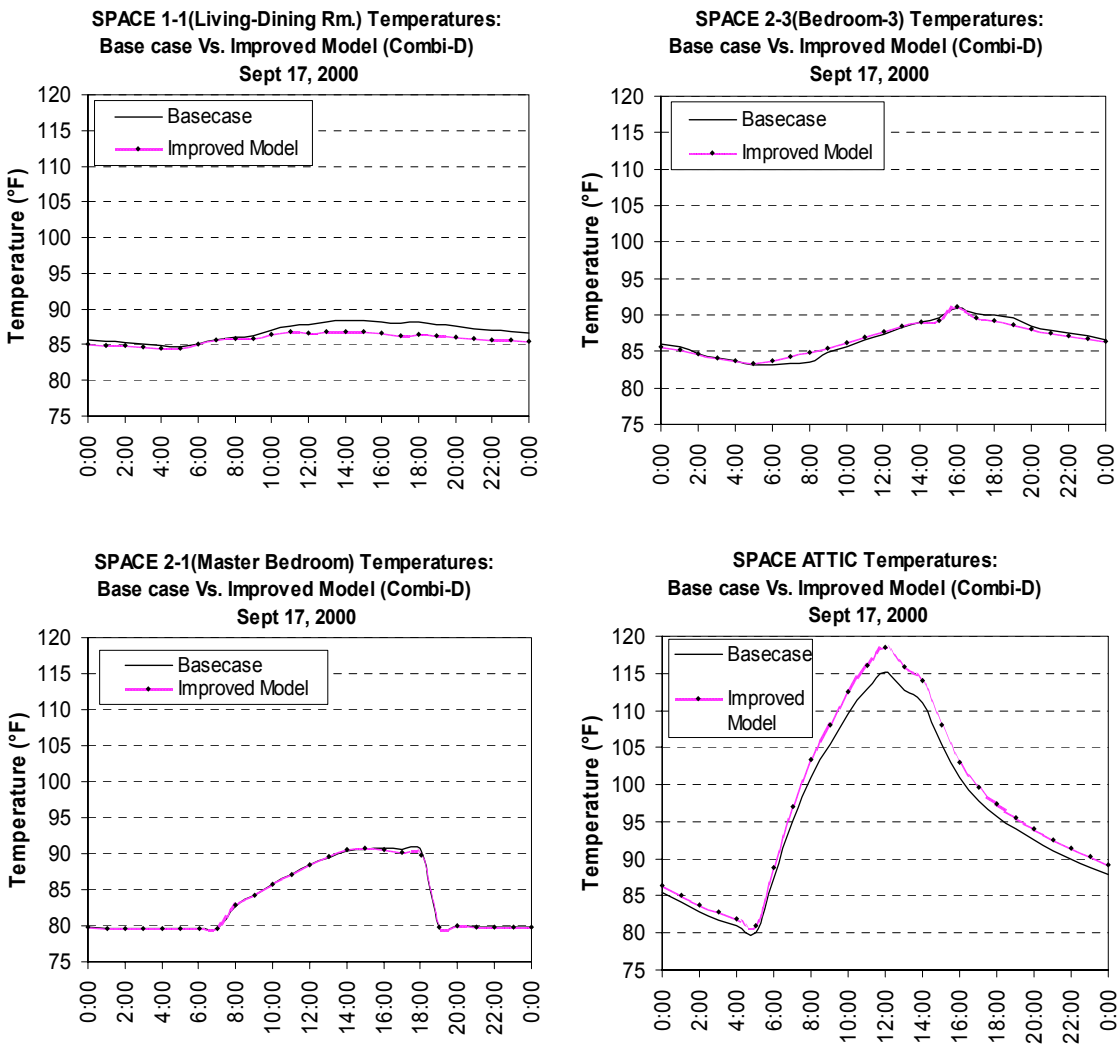


Figure 7.57 *Comparisons between Base Case and Combination D Space Temperatures.*

7.3.18 Combination E: Combination D Combined with the Hybrid PV-T^2 Collector System

Combination E combines Combination D with Renewable Energy Technology 1 (hybrid PV-T^2 collector system). Figure 7.58 shows the annual energy use of the Combination E, as compared to that of the base case. The BEPS of the Combination E as compared to the base case is shown in Table 7.28. From Figure 7.58 and Table 7.29, it can be seen that the

energy used for area light, equipment, space cooling and ventilation fans decrease by 27.0, 51.7, 44.2 and 41.2 percent, respectively. All of the energy used for DHW and pump was reduced by 100 percent, since the hybrid PV-T^2 collector system could supply all of the DHW demands and pump electricity use. This resulted in a decrease of total energy consumption by 64.9 percent, or 3424 kWh per year. Thus, this is a very significant reduction in the building's energy consumption as compared to Combination A to D, which had the annual energy reduction of approximately 21 percent.

For space temperatures, in general, the temperatures in the living space are similar to those of Combination D as shown in the lower left graph of Figure 7.58. However, the attic temperatures were reduced in the daytime due to the effect of shading from the hybrid PV-T^2 array as shown in Figure 7.59.

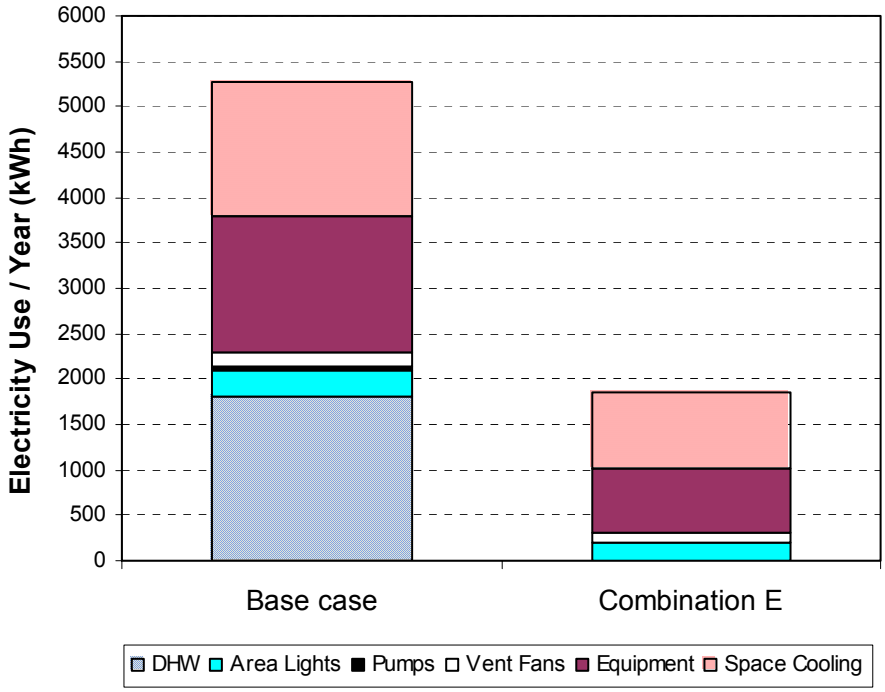


Figure 7.58 *Comparison of Annual Energy Use of Base Case and Combination E.*

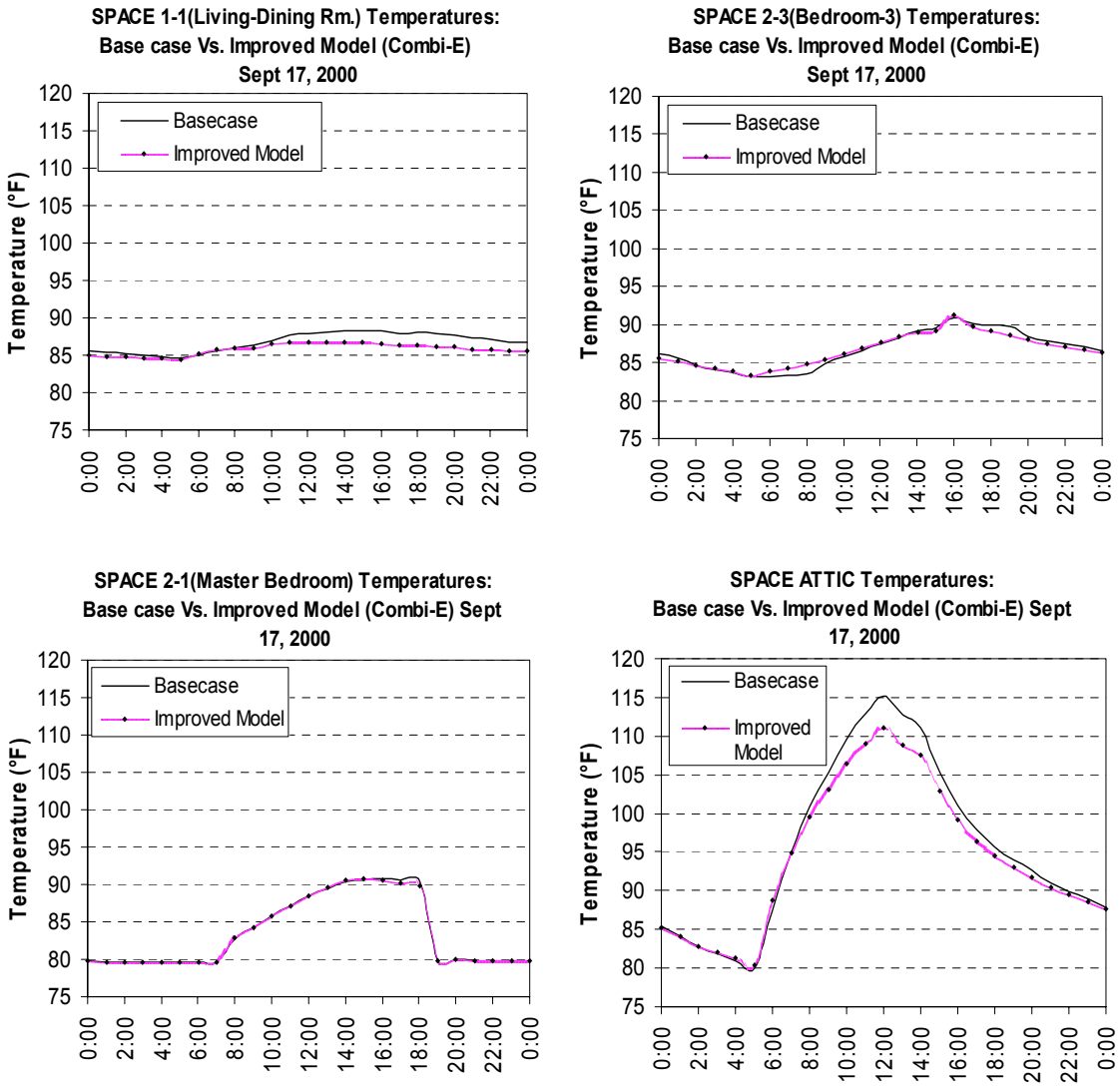


Figure 7.59 *Comparisons between Base Case and Combination E Space Temperatures.*

TABLE 7.29

Building Energy Performance Summary: Base Case vs. Combination E

Category of Use	Annual Site Energy Consumptions			
	Base case	Improved Model	Energy Saved	
	kWh	kWh	kWh	(%)
Area Lights	280	204	76	27.0
Equipment	1497	723	774	51.7
Space Cooling	1480	826	654	44.2
Pumps	46	0	46	100.0
Vent Fans	165	97	68	41.2
Domestic Hot Water	1807	0	1807	100.0
Total	**5275**	**1851**	**3424**	**64.9**

7.3.19 Combination F: Combination D Combined with a Photovoltaic System

Combination F combines Combination D with Renewable Energy Technology 2 (PV system). Figure 7.60 shows the annual energy use of the Combination F, as compared to that of the base case. The BEPS of the Combination F as compared to the base case is shown in Table 7.30. From Figure 7.60 and Table 7.30, it can be seen that the energy used for area light, equipment, space cooling and ventilation fans decrease by 27.0, 90, 43.3 and 43 percent, respectively. The pump energy use was reduced by 100 percent. There was no energy reduction in the DHW, since there was no supplemental thermal energy from the PV system. This resulted in a decrease of total energy consumption by 41.4 percent, or 2,181 kWh per year. Thus, this is a significant reduction in the building's energy consumption as compared to Combination A to D which had the annual energy reduction of approximately 21 percent. However, the reduction of energy use was less than that of Combination E (64.9 percent) which could supply all DHW requirements.

For space temperatures, in general, the temperatures in the master bedroom and bedroom-3 were slightly lower than those of Combination E as shown in the lower left graph of Figure 7.61. However, the living room temperatures were not changed. The attic temperatures were dramatically reduced in the daytime due to the effect of shading from the PV array shown in Figure 7.61.

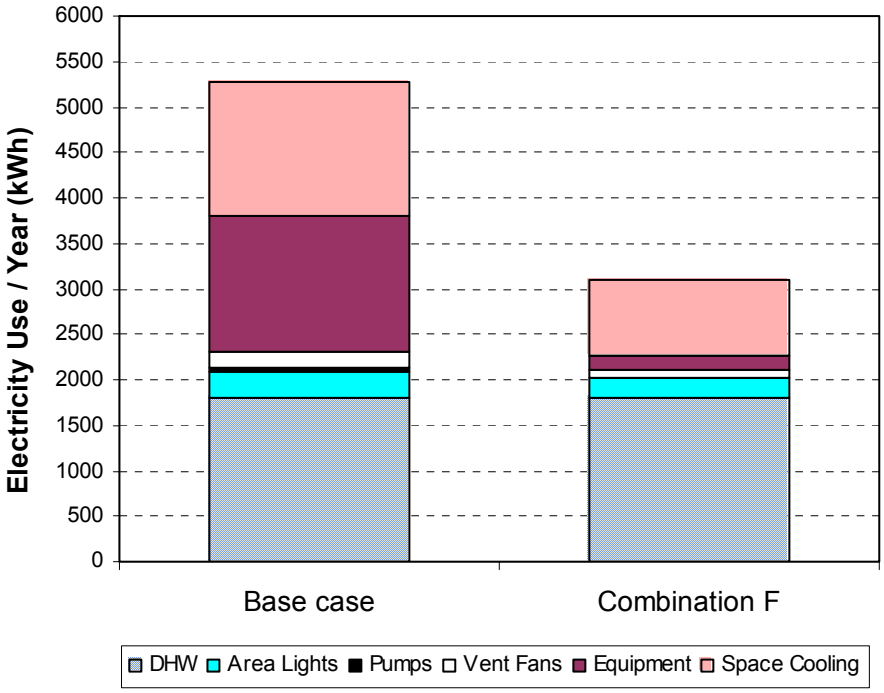


Figure 7.60 *Comparison of the Annual Energy Use of Base Case and Energy Efficiency Combination F.*

TABLE 7.30

Building Energy Performance Summary: Base Case vs. Combination F

Category of Use	Annual Site Energy Consumptions			
	Base case	Improved Model	Energy Saved	
	kWh	kWh	kWh	(%)
Area Lights	280	204	76	27.0
Equipment	1497	150	1347	90.0
Space Cooling	1480	838	642	43.4
Pumps	46	0	46	100.0
Vent Fans	165	94	71	43.0
Domestic Hot Water	1807	1807	0	0.0
Total	**5275**	**3094**	**2181**	**41.4**

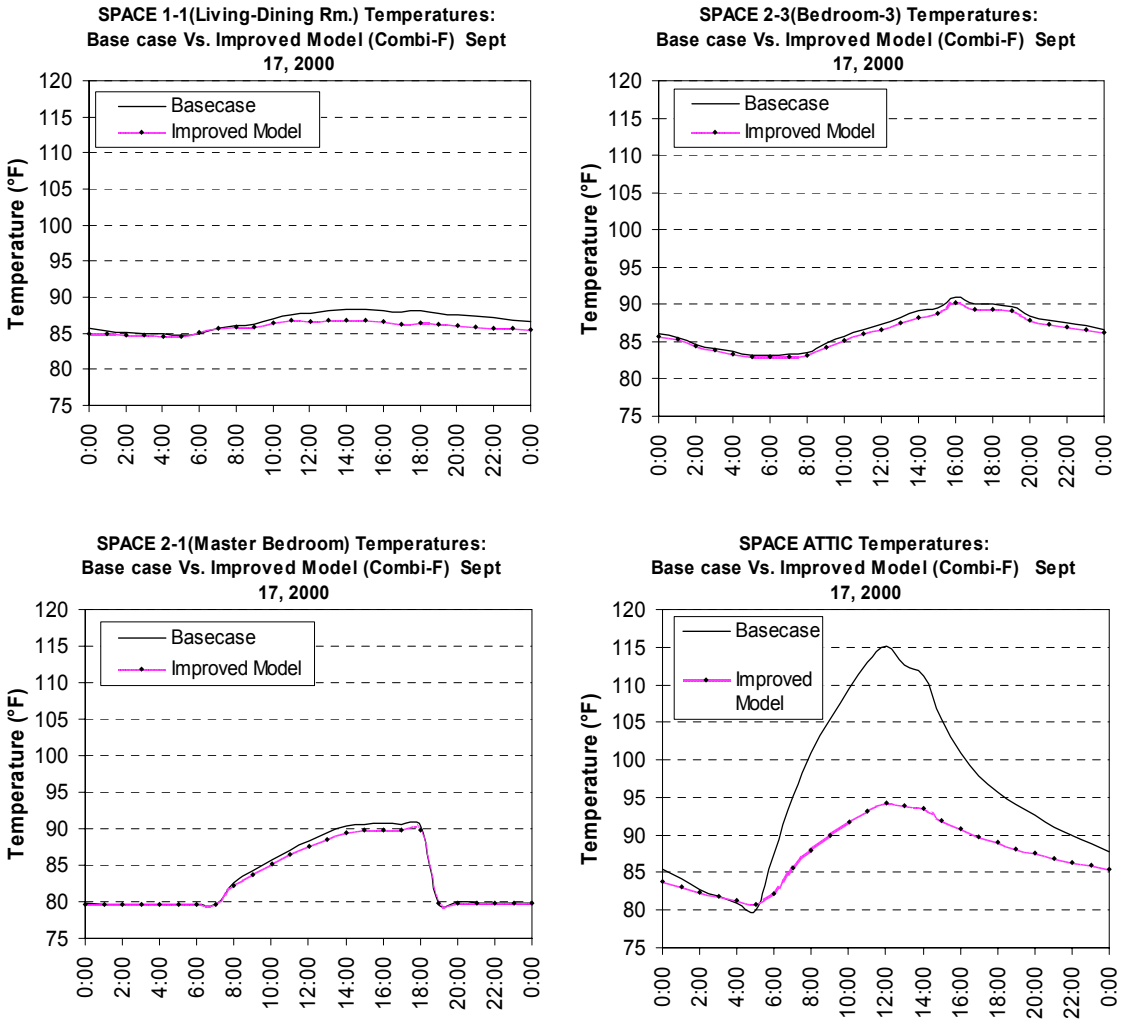


Figure 7.61 *Comparisons between Base Case and Combination F Space Temperatures.*

7.3.20 Combination G: Combination D Combined with the Hybrid PV-T^2 Collector System and a Photovoltaic System

Combination G combines Combination D with both Renewable Energy Technology 1 (hybrid PV-T^2 collector system) and Renewable Energy Technology 2 (photovoltaic system). Figure 7.62 shows the annual energy use of the Combination G, as compared to that of the base case. The BEPS of the Combination G as compared to the base case is shown in Table 7.31.

From Figure 7.62 and Table 7.31, it can be seen that the energy used for area lights, equipment, space cooling and ventilation fans decrease by 27.0, 76.6, 46.1 and 42.4 percent, respectively. All of the energy used for the DHW and the pumps was reduced by 100 percent, since the hybrid PV-T^2 collector system could supply all of the DHW demands and pump electricity use. This resulted in a decrease of total energy consumption by 72.6 percent, or 3,829 kWh per year. Thus, this is a very significant reduction in the building's energy consumption as compared to Combination A to D which had the annual energy reduction of approximately 21 percent, and to Combination E and F that reduced the annual energy uses by 64.9 and 41.4 percent, respectively. The space temperatures of Combination G were identical to those of Combination F, since the whole roof area was covered in both combinations.

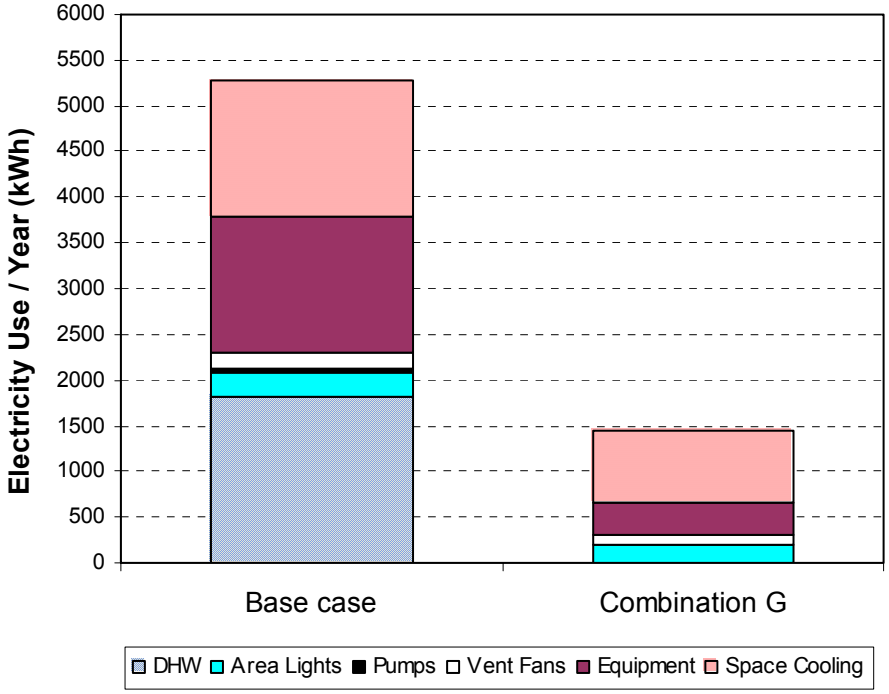


Figure 7.62 *Comparison of Annual Energy Use of Base Case and Energy Efficiency Combination G.*

TABLE 7.31

Building Energy Performance Summary: Base Case vs. Combination G

Category of Use	Annual Site Energy Consumptions			
	Base case	Improved Model	Energy Saved	
	kWh	kWh	kWh	(%)
Area Lights	280	204	76	27.0
Equipment	1497	350	1147	76.6
Space Cooling	1480	797	683	46.1
Pumps	46	0	46	100.0
Vent Fans	165	95	70	42.4
Domestic Hot Water	1807	0	1807	100.0
Total	**5275**	**1446**	**3829**	**72.6**

7.4 Comparison of the Results

The results of Strategies 1-10, Renewable Energy Technologies (RETs) 1-4, and Combinations A-G are compared in Table 7.32 and Figure 7.63. From the table, for the individual energy efficiency strategies (excluding the RETs 1-4), Strategy 3-4 (insulated light-weight concrete block walls) was the most effective strategies (9.08 percent of total energy reduction). Strategies 3-2, 3-3, and 3-4 were also in ranked high (4th, 3rd, 2nd, respectively). The energy reductions by the renewable energy technologies as compared to the individual energy efficiency strategies, (RET 3), which is the combined PV-T^2 and PV systems, was ranked in first place (51.37 percent of the building's energy reduction). The PV-T^2 collector system (RET 1) and the flat plate solar collector system (RET 2) were ranked in second place and third place, respectively (a reduction of 43.25 percent and 26.71 percent of the building's energy use respectively). The PV system was ranked in fourth place, which reduced energy use by 23.30 percent). It is interesting that RET 4, which is the improvement of the building by the flat plate solar collector system, could reduce energy use more that RET 2 (the PV system). This is because RET 4 could supply all the DHW needs, which is highest energy use in all categories, while RET 2 could not supply electricity to the DHW system since the DHW was used in the early morning and evening.

Comparisons of the results of Combination A to G are also presented in Table 7.32. From the table, Combination G was ranked in the 1st place which was able to reduce the

building's energy use by 72.58 percent. Combination E and F were ranked in the 2nd and 3rd (64.92 and 41.35 percent, respectively).

TABLE 7.32

Building Energy Performance Summary: Base Case vs. All Energy Efficiency Measures, Renewable Energy Technology 1 to 4, and Combinations A to G

Energy Efficiency Measures	Annual Energy Consumption (kWh)							Annual Energy Saving			
	Area Lights	Equip.	Space Cooling	Pumps	Vent Fans	DHW	Total	Total Saving (kWh)	Total Saving (%)	Stra 1-9 Rank	Rank (All)
Base-case	280	1497	1480	46	165	1807	**5275**	–	–	–	
Strategy 1-1 Insulation behind the roof tiles (R-7)	280	1497	1454	46	163	1807	**5247**	28	0.53	10	14
Strategy 1-2 Insulation behind the roof tiles (R-14)	280	1497	1443	46	160	1807	**5233**	42	0.80	9	13
Strategy 2 Increase insulation on the 2nd floor's ceiling	280	1497	1431	46	160	1807	**5221**	54	1.02	7	11
Strategy 3-1 High R-value light weight concrete wall (4")	280	1497	1117	46	117	1807	**4864**	411	7.79	4	8
Strategy 3-2 High R-value light weight concrete wall (6")	280	1497	1113	46	116	1807	**4859**	416	7.89	3	7
Strategy 3-3 3-1 + Insulation on the exterior	280	1497	1101	46	116	1807	**4847**	428	8.11	2	6
Strategy 3-4 3-1 + Insulation on the interior	280	1497	1056	46	110	1807	**4796**	479	9.08	1	5
Strategy 4 Double-pane Low-e windows	280	1497	1488	46	166	1807	**5284**	-9	-0.17	12	16
Strategy 5 Shading devices on windows	280	1497	1455	46	162	1807	**5247**	28	0.53	10	14
Strategy 6-1 High Thermal Mass Wall (8" brick)	280	1497	1532	46	177	1807	**5339**	-64	-1.21	14	18
Strategy 6-2 High Thermal Mass Wall (12" brick)	280	1497	1486	46	170	1807	**5286**	-11	-0.21	13	17
Strategy 7 High energy efficient air-conditioning systems	280	1497	1293	46	165	1807	**5088**	187	3.55	6	10
Strategy 8 Electronic Ballasts	238	1497	1477	46	165	1807	**5230**	45	0.85	8	12
Strategy 9 High energy efficient refrigerator	280	1105	1469	46	164	1807	**4871**	404	7.66	5	9
Strategy 10 (RET 1) Supplemental Energy from the Hybrid PV-T^2 system	240	1121.03	1468	0	164	0	**2993**	2282	43.25		2
Strategy 11 (RET 2) Supplemental Electricity from the PV system	240	407.74	1431	0	160	1807	**4046**	1229	23.30		4
Strategy 12 (RET 3) Supplemental Electricity from the PV-T^2 and PV systems	240	747.61	1418	0	159	0	**2565**	2710	51.37		1
Strategy 13 (RET 4) Supplemental Energy from a flat plate solar collector	240	1497	1480	484	165	0	**3866**	1409	26.71		3
										Rank of Combi.	
Combination A Strategy 2 + 3-4 + 7 + 8 + 9	238	1105	856	46	103	1807	**4155**	1121	21.24	7	
Combination B Combination A + Strategy 4	238	1105	842	46	99	1807	**4137**	1139	21.58	5	
Combination C Combination A + Strategy 5	238	1105	853	46	102	1807	**4151**	1125	21.32	6	
Combination D Combination A + Strategy 4 and 5	238	1105	838	46	98	1807	**4132**	1144	21.68	4	
Combination E Combi. D + Sup Energy from Hybrid PV-T^2	204	723	826	0	97	0	**1851**	3424	64.92	2	
Combination F Combi. D + Sup Energy from PV	204	150	838	0	94	1807	**3094**	2181	41.35	3	
Combination G Combi. D + Sup Energy from Hybrid PV-T^2 and PV	204	350	797	0	95	0	**1446**	3829	72.58	1	

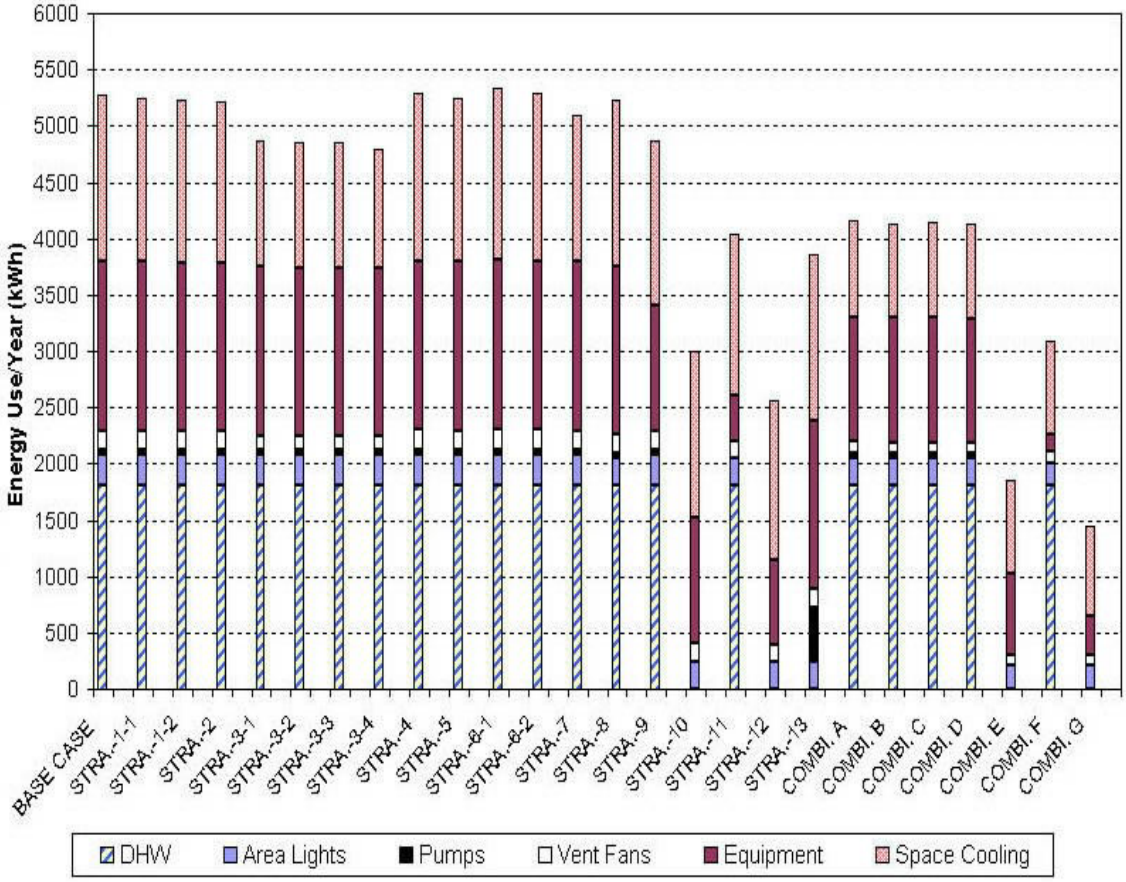


Figure 7.63 *Comparison of Annual Energy Consumptions of Base Case and All Energy Efficiency Measures: January to December, 2000.*

7.5 Summary

This chapter has presented and discussed the results of the simulation of the case-study house which include the calibration of the model against both the measured data and utility bills. This chapter also presented the results of the investigation into energy efficient strategies, renewable energy technologies, and combinations of those used to improve the case-study model. The energy reductions by each strategy and the combinations were presented. The comparisons of the energy efficient strategies and renewable energy technologies as well as their combinations were reported.

CHAPTER VIII

ECONOMIC ANALYSIS

This chapter presents an economic analysis of the case-study house that compares the base-case building with the same building improved by the energy efficiency strategies and renewable energy technologies discussed in the previous chapter. This chapter presents an analysis of each of the energy efficiency strategies and renewable energy technologies, as well as combinations of the strategies. This study uses the annualized life-cycle cost method described in ASHRAE (1999) and Haberl (1993).

8.1 Inputs for the Economic Analysis

The primary input data for the economic analysis includes the owning costs, operating cost, and maintenance costs. Other elements that were established or defined to calculate annual owning costs, include: study period length, discount rate (id), inflation rate (j), mortgage rate (im), and periodic costs such as insurance, and property tax. All of those factors, which are presented in Table 8.1, are discussed in Section 8.1.1, except the first cost which is discussed in Section 8.1.2.

The operating costs included the cost of electricity. The annual electricity use was obtained from the analysis of building energy use (Chapter VII), which included the annual electricity use of the base-case house and the improvements represented by Strategies 1 to 9, Strategies 10 to 13 (Renewable Energy Technologies 1 to 4), and Combinations A to G. The cost of electricity was calculated from the amount of electricity used (kWh) and the rate of electricity consumption charge for Thai residential building (approximately $ 0.075 per kWh). The annual electricity cost is presented in Appendix G. Maintenance costs, which include replacement costs, are summarized in Table 8.2 in Section 8.13.

8.1.1 Economic Factors

This section discusses the economic factors that were used in the economic analysis. These factors include the study period, discount rate (id), inflation rate (j), mortgage rate (im),

depreciation, and other periodic costs such as insurance and property tax. These factors were established using various source of information including Thailand's published economic statistics (Table 8.1).

Table 8.1

Summary of the Economic Factors in the Analysis

Life of the Project	25 Yrs
Investment Tax Credit	$0
Discount Rate (id)	3.0 %
Inflation Rate (j)	1.80 %
Fuel Inflation Rate (je)	4.0 %
Mortgage Rate (im)	4.0 %
Income Tax	5.0 %
Property Tax	0.0 %

The life of the project or study period was assumed to be 25 years. No investment tax credits were applied in this analysis, since there were no tax incentives for residential energy conservation or renewable energy use by the time this study was performed. Thailand's inflation rate (1.8 percent) was obtained from the Bank of Thailand (BOT, 2004). The fuel inflation rate (je) was 4.0 percent (BOT, 2004). There were many mortgage rates in Thailand, which vary from year to year; a fixed mortgage rate of 4 percent was used. The house was exempted from property taxes since it was a small residential building, therefore no taxes were assumed.

8.1.2 First Year Cost

Table 8.2 shows the initial costs of the base-case house and the increased costs due to the improvement from the energy efficiency strategies and renewable energy systems. Total first year costs of each strategy or renewable energy system were from the summation of the base-case house's first year cost and the increased cost of each improvement. The cost of the base-case house included the costs of land, building, two air conditioning systems, and two

refrigerators. Details of the base-case costs and the increased costs are presented in Appendix G.

Table 8.2

Summary of the Total First Year Cost of the Energy Efficiency Strategies and Renewable Energy Technology

Energy Efficiency Strategies and Renewable Energy Technology	Increased Cost	Total First Year Cost
Base-Case House		$63,163
2nd Floor Ceiling Insulation	$563	$63,726
Insulated Light-Weight Concrete Block Wall	$4,364	$67,527
Low-E Windows	$2,098	$65,261
Shading Devices	$457	$63,620
SEER-12 Air-Conditioning Systems	$749	$63,912
Electronic Ballasts	$182	$63,345
High Energy Efficient Refrigerators	$125	$63,288
PV-T^2 System	$30,994	$94,157
PV System	$57,139	$120,303
PV-T^2 System and PV System	$72,158	$135,322
Flat-Plate Solar Collector (Double Glazing)	$16,224	$79,387

8.1.3 Maintenance and Replacement Costs

Table 8.3 shows annual maintenance and replacement costs of the base-case house, energy efficiency strategies, and renewable energy systems. Annual maintenance cost of the base-case house ($ 50) was for the air conditioning systems that need regular maintenance such as filter cleaning. The annual replacement cost of the base-case house ($20) was estimated to account for the replacement of lighting system, such as incandescent lamps (task lights), and fluorescent lamps. The base-case house's replacement cost at the end of the 15th year was for two air conditioning systems ($1,125) and magnetic ballasts ($77). For this analysis, the base-case air conditioning systems were assumed to be SEER-10–similar to the existing systems. At the end of the 20th year, the base-case house's replacement cost of $750 was used to account for the replacement of the two refrigerators.

Table 8.3

Summary of the Maintenance and Replacement Costs of the Energy Efficient Strategies and Renewable Energy Technology Systems

Energy Efficiency Strategies and Renewable Energy Technology	Annual Maintenance Costs	Replacement Costs	Replacement Year
Base-Case House	$50.00	$20.00	Annually
		$1,202.00	at 15th Years
		$625.00	at 20th Years
2nd Floor Ceiling's Insulation	$0.00	$0.00	
Insulated Light-Weight Concrete Block Walls	$0.00	$0.00	
Low-E Windows	$0.00	$0.00	
Shading Devices	$0.00	$0.00	
12 SEER Air-Conditioning Systems	$50.00	$1,873.77	at 15th Years
Electronic Ballasts	$0.00	$258.50	at 15th Years
High Energy Efficient Refrigerators	$0.00	$750.00	at 20th Years
PV-T^2 System	$50.00	$505.00	$325 at 10th and $180 at 20th Years
PV System	$50.00	$285.00	$225 at 10th and $60 at 20th Years
PV-T^2 System and PV System	$100.00	$790.00	$550 at 10th and $220 at 20th Years
Flat-Plate Solar Collector System	$50.00	$220.00	$100 at 10th and $120 at 20th Years

The annual maintenance and replacement costs of energy efficiency strategies and renewable energy systems are shown in Table 8.3. As shown in Table 8.3, the second floor ceiling insulation, insulated light-weight concrete block walls, Low-e windows, and shading devices were assumed to have no annual maintenance and replacement costs. The electronic ballasts for the fluorescent lamps and the energy efficient refrigerators also required no annual maintenance. However, a replacement at the end of 15th year ($259) and the 20th year ($750) were assumed, respectively. For the SEER-12 air conditioning systems, the annual maintenance cost was $50.00. Since the estimated service life of a residential split-type air conditioning system is 15 years (ASHRAE, 1999), the replacement of the air conditioning systems (with the same SEER) was projected to occur at the end of year 15 ($1874).

Photovoltaic systems normally require only surface cleaning for the photovoltaic array. Dust deposits lower the efficiency of the photovoltaic panel, thus decreasing output energy from the system. Therefore, regular cleaning of the PV surface is necessary, however during the raining season (from May to September), the cleaning may not be necessary since the rain cleans the panels. An annual maintenance cost of $50.00 was estimated for the cleaning of the photovoltaic arrays. A similar maintenance cost for the hybrid PV-T^2 collector system and the Flat-Plate Solar Collector system was assumed ($50.00 per year for each system).

Replacement of a PV or PV-T^2 module (120 Watts) was expected at the 10th year and 20th. The cost of the polycrystalline silicon PV modules was projected to decrease from $ 3.00 per Watt (as of 2002) to $ 2.00 per Watt in 2010 (Maycock, 2004). Thus, the cost was projected to decrease at the rate of $0.125 per Watt per year. The first replacement of the PV module (at the 10th year) would be in 2014. There was no projection of the PV module cost beyond 2010 in this report. In this study, the cost of the PV module is expected to be $1.5 per Watt which is lower than the cost in 2010 (expected a decrease rate of $0.125 per Watt per year).

From a report of the Department of Energy (DOE, 2004), the cost of crystalline-silicon PV module was estimated to be $0.90 per Watt in 2020 and $0.53 per Watt in 2030. The second replacement of the PV module (at the 20th year) will be in 2024. From the estimated cost of the PV module in 2020 and 2030, the cost of the PV module in 2024 will be around $0.7 per Watt. The cost of a polycrystalline silicon PV module is approximately $0.30 per Watt lower than the cost of a crystalline-silicon PV module (Maycock, 2004). Thus, the cost of the polycrystalline silicon PV module in 2024 will be $0.4 per Watt.

Therefore, the cost of the PV module would be $ 180 for the 10th year (2014) and $ 48 for the 20th year (2024). The initial installation cost including power-related Balance of System (BOS) (i.e., DC-to-AC inverter, maximum power point tracker, and wiring) and area-related BOS (i.e., support structure of the PV array) costs approximately 40 percent and 28 percent of the PV module cost, respectively (DOE, 2004). The replacement of the PV module requires some wiring. The inverter, the tracker and the support structure of the PV array are not expected to be replaced. Thus, the installation cost of a replacement PV module was estimated to be lower than 40 percent of the PV module cost. In this study, the installation cost of the PV module was expected to be around 25 percent of the PV module cost (i.e., $45 for the 10th year and $12 for the 20th year).

From the above discussion about the cost of the PV modules and the installation cost, the total replacement costs of the PV module were estimated to $225 and $60 for the 10th year (2014) and 20th year (2024), respectively. Similar replacement costs for the hybrid PV-T^2 collector system were assumed ($225 and $60 for the 10th year (2014) and 20th year (2024), respectively). However, the hot water pump was planned to be replaced at 10th year ($100) and 20th year ($120). Therefore, the replacement cost of the hybrid PV-T^2 collector system was $325 at 10th year and $180 at 20th year. For the replacement cost of the Flat-Plate Solar Collector System, the hot water pump was planned to be replaced at 10th year ($100) and 20th year ($120).

8.2 Discussion of the Results of the Life-Cycle Cost Analysis of the Individual Energy Efficiency Strategies, and the Renewable Energy Systems

In Chapter VII, the results of the energy efficiency strategies and the renewable energy systems was discussed including details about the amount of electricity saved and the impact on indoor air temperatures. This section discusses the results of the life-cycle cost analysis of the individual energy efficiency strategies and renewable energy strategies.

From the nine energy efficiency strategies, there were seven energy efficiency strategies that were selected to be analyzed in the economic analysis. An economic analysis was also performed on all renewable energy systems that were analyzed in Chapter VII. Those seven energy efficiency strategies and renewable energy systems evaluated with the economic analysis are listed below:

- Strategy 2: Insulation on 2nd Floor Ceiling
- Strategy 3-4: Insulated Light-weight Concrete Block Walls
- Strategy 4: Low-e Windows
- Strategy 5: Shading Devices
- Strategy 7: SEER-12 Air Conditioning Systems
- Strategy 8: Electronic Ballasts
- Strategy 9: High Efficiency Refrigerators

The two strategies that were not effective either in the reduction of building energy use or the living space's temperature were Strategies 1 and 6 (Strategy 1-1: R-7 insulation underside the roof tiles, Strategy 1-2: R-14 insulation underside the roof tiles, Strategy 6-1: 8-inch High Thermal Mass Wall, and Strategy 6-2: 12-inch High Thermal Mass Wall). Strategies 1-1 and 1-2 dramatically reduced the attic's temperature, but they had little impact on the living space's temperature and building energy use (less than one percent of building energy use). Thermal mass walls (Strategy 6-1 and 6-2) were also not included in this analysis. From the results of Strategy 6-1 and 6-2 in Chapter VII, although daytime space temperatures of the living spaces were significantly reduced, the building energy use was actually slightly increased due to the

nighttime temperature rise in the living space.

The analyses of the individual energy efficiency strategies and renewable energy strategies are presented in the following sections. Comparison of the results using a life-cycle cost analysis is presented in Section 8.3.

8.2.1 Base-Case Scenario

The base-case scenario represents the "as is" condition of the case-study house. The existing condition of the case-study house was discussed in Chapter V. The base-case house cost $63,163 which was estimated from the current cost per square foot of Thai residential buildings in 2004 (Bureau of Budget, 2004). Of this amount, the building cost $47,548 and the land cost $15,615. The cost of the base-case house was also included the cost of two air conditioning systems ($1,125) and two refrigerators ($625). The annual energy use for the house was 5,275 kWh. The annual cost of electricity was $396. The maintenance and replacement costs of the base-case house were discussed in Section 8.1.3. From the results of the analysis, which is presented in Appendix G, the annualized life-cycle cost of the base-case house was -$2,818.

8.2.2 Strategy 2: Improvement of 2nd Floor Ceiling's Insulation

Upgrading the insulation on the 2nd floor ceiling from R-11 to R-28 would add $563 to the base-case cost. This resulted in an increase of the total cost from $47,548 to $48,111. The maintenance and replacement costs did not increased from the base-case scenario, since there were no maintenance and replacement cost required for the insulation during the period of the analysis. The annual cost of electricity was $392 which was $4 lower than the base-case simulation. The annualized life-cycle cost of the Strategy 2 is -$2,832, which is an annualized increase of $14 from the annualized life-cycle cost of the base-case house.

8.2.3 Strategy 3-4: Insulated Light-Weight Concrete Block Walls

The base-case's 4" brick walls cost $3,185 and the insulated light-weight concrete block walls cost $7,549, which resulted in an increase cost of $4,364 from the base-case house. The maintenance and replacement costs of Strategy 3-4 were similar to those of the base-case scenario, since there were no maintenance and replacement costs required for the insulated

light-weight concrete block walls during the period of the analysis. The annual cost of electricity was $360 which was $36 lower than the base-case simulation. The annualized life-cycle cost of the Strategy 3-4 was -$2,963, which was an increase of $145 above the annualized life-cycle cost of the base-case house.

8.2.4 Strategy 4: Low-E Windows

The Low-e windows cost $3,188 which is an increase of $2,098 from the existing windows (single-pane glass windows costing $1090). The maintenance and replacement costs did not increased from the base-case scenario, since there were no maintenance and replacement costs required for the Low-e windows during the period of the analysis. The annual cost of electricity was $396 which was approximately equal to that of the base-case simulation. The simulated annualized life-cycle cost of the Strategy 4 was -$2,907, which was an annualized increase of $89 above the annualized life-cycle cost of the base-case house.

8.2.5 Strategy 5: Shading Devices

The shading devices were estimated to cost an additional $475. This resulted in a total first cost of $63,620. There were no maintenance and replacement costs for the shading devices. The annual cost of electricity was $393 which was $2 lower than the base-case. The simulated annualized life-cycle cost of the Strategy 5 was -$2,829, which was an annualized increase of $11 from the annualized life-cycle cost of the base-case house.

8.2.6 Strategy 7: SEER-12 Air Conditioning Systems

The two SEER-12 air conditioning systems cost $1,874 which is an increase of $749 from the existing air conditioning systems (SEER-10). The annual maintenance and replacement costs were assumed not to increase from the base-case scenario ($70.00), since there were no extra maintenance costs for the SEER-12 compared to SEER-10 air conditioning systems. The replacement of the air conditioning systems at the year 15th would cost $1,874 (approximately $750 more than the SEER-10 air conditioning systems). At the year 15, higher SEER split-type air conditioning systems may be available. However, this study assumed that the replacement in the 15th year use SEER-12 systems. For the SEER-12 system the annual cost of electricity was $382 which was $14.00 lower than the base case. The annualized life-cycle

cost of the Strategy 7 was -$2,852 which was an increase of $40 from the annualized life-cycle cost of the base-case house.

8.2.7 Strategy 8: Electronic Ballasts

The base-case house has eleven fluorescent lamps that include magnetic ballasts. The cost of eleven electronic ballasts would be $259, which was $182 higher than the cost of existing magnetic ballasts ($77). The annual maintenance and replacement costs were assumed not to increase from the base-case scenario ($70), since there were no extra annual maintenance and replacement costs for the electronic ballasts. The life of a ballast was assumed to be approximately 15 years. The replacement cost of the electronic ballasts at the year 15th with new electronic ballasts was assumed to be $258. The simulated annual cost of electricity for the electronic ballasts was $392 which was $3.30 lower than the base-case costs. The simulated annualized life-cycle cost of Strategy 8 was -$2,818 which was an annualized increase of $6 from the annualized life-cycle cost of the base-case house.

8.2.8 Strategy 9: High Energy Efficient Refrigerators

As mentioned in Chapter V and VII, the base-case house had two refrigerators. The replacement of the existing refrigerators with high energy efficiency refrigerators would cost $125 more than the base-case house. The annual maintenance and replacement costs were assumed not to increase from the base-case scenario ($70), since no extra annual maintenance and replacement costs for the new refrigerators was assumed. The life of a refrigerator was assumed to be 20 years. The replacement cost of the refrigerators at the year 20th would be $750. The simulated annual cost of electricity was $365, which was $30.30 lower than the base-case simulation. The annualized life-cycle cost of the Strategy 6 was -$2,780, which was a decrease of $32 from the annualized life-cycle cost of the base-case house.

8.2.9 Strategy 10: Hybrid PV-T^2 Collector System

The cost of the hybrid PV-T^2 collector system was estimated as $30,994. This would increase the first cost of the house from $63,163 to $94,157. The annual maintenance cost of the hybrid PV-T^2 collector system was estimated as $50.00. The replacement costs expected at the 10th year ($325) and in the 20th year ($160) were as discussed in Section 8.1.3. From the

results of the supplemental energy analysis in Chapter VII, the hybrid PV-T^2 collector system could reduce the base-case's annual energy use from 5,275 kWh to 2,993 kWh, which reduced the simulated annual electricity cost from $396 to $225. The annualized life-cycle cost was -$4,757 which was an annualized increase of $1,244 from the annualized life-cycle cost of the base-case house.

8.2.10 Strategy 11: Photovoltaic System

The PV modules that were installed on all the available area of the roof (1053 ft^2) was estimated to cost $41,165. This would increase the first cost of the house from $63,163 to $104,328. The annual maintenance cost of the PV system was estimated as $50.00. Replacement costs were expected at the 10th year ($225.00) and 20th year ($60) as discussed in Section 8.1.3. From the results of the supplemental energy analysis in Chapter VII, the PV system could supply 1,229 kWh per year, which reduced the base-case's annual energy demand from the grid from 5,275 kWh to 4,046 kWh. Therefore, the annual electricity cost reduced from $395.6 to $303.5. The annualized life-cycle cost was -$6,070 which was an annualized increase of $2,557 from the annualized life-cycle cost of the base-case house.

8.2.11 Strategy 12: Hybrid PV-T^2 Collector System and Photovoltaic System

The cost of the hybrid PV-T^2 collector system was estimated as $30,934. The PV system, which covered the rest area of the roof (759 ft^2), was estimated as $41,165. Thus the total first cost of both systems was $72,158. This would increase the first cost of the house from $63,133 to $135,322. The annual maintenance cost of the two systems was $100.00. The replacement costs, which are the summation of the replacement costs of both systems, were expected to be $550 in the 10th year and $220 in the 20th year. From the results of the supplemental energy analysis in Chapter VII, both systems could supply 2,710 kWh of electricity, which reduced the base-case's annual energy demand from the grid by 51.37 percent (from 5,275 kWh to 2,565 kWh). This resulted in the reduction of the annual electricity cost from $396 to $192. The annualized life-cycle cost was -$6,735, which was an annualized increase of $3,222 from the annualized life-cycle cost of the base-case house.

8.2.12 Strategy 13: Flat-Plate Solar Collector System

The cost of the Flat-Plate solar collector system was estimated as $16,224. This would increase the first cost of the house from $63,163 to $79,387. The annual maintenance cost of the Flat-Plate solar collector system was estimated as $50.00. The replacement costs expected at the 10th year ($100) and in the 20th year ($120) were as discussed in Section 8.1.3. From the results of the supplemental energy analysis in Chapter VII, the Flat-Plate solar collector system could reduce the base-case's annual energy use from 5,275 kWh to 3,866 kWh, which reduced the simulated annual electricity cost from $396 to $290. The annualized life-cycle cost was $4,165 which was an annualized increase of $652 from the annualized life-cycle cost of the base-case house.

8.3 Comparisons of the Results of the Life-Cycle Cost Analysis of Individual Energy Efficiency Strategies and Renewable Energy Systems

This section compares the results of the life-cycle cost analysis of the base-case house with the individual energy efficiency strategies as well as the renewable energy systems. Figure 8.1 presents the first cost of the base-case house as compared to those of the energy efficiency strategies and the renewable energy systems. From Figure 8.1, in general, the first costs of energy efficiency strategies were not significantly different from the first cost of the base-case house. However, the first costs of the renewable energy systems were significantly higher than the cost of the base-case house as can be seen in the Figure 8.1.

For the energy efficiency strategies, the cost of light-weight concrete walls was the highest first cost among the energy efficiency strategies. The second highest cost of the energy efficiency strategies was the low-e windows. Other strategies did not substantially increase the first cost of the base-case house.

For the renewable energy systems, the cost of the Flat-Plate solar collector system was relatively lower than other renewable energy systems since it is the only system that had no PV panel installed. The cost of the hybrid PV-T^2 collector system was higher than the Flat-Plate solar collector system, but lower than other renewable energy systems. This was because the hybrid PV-T^2 system required larger area to meet the DHW demand. The total cost of the photovoltaic system was approximately equal to the cost of the base-case house. This high cost was due to the fact that the PV modules were installed on the whole area of the roof. The cost of the PV modules was very high in Thailand. The PV modules need to be imported from the

manufactures in foreign countries such as the United States and Japan, since currently there were no PV manufactures in Thailand. The highest first cost among all renewable energy systems and all strategies was the combination of the hybrid PV-T^2 collector system and the PV system.

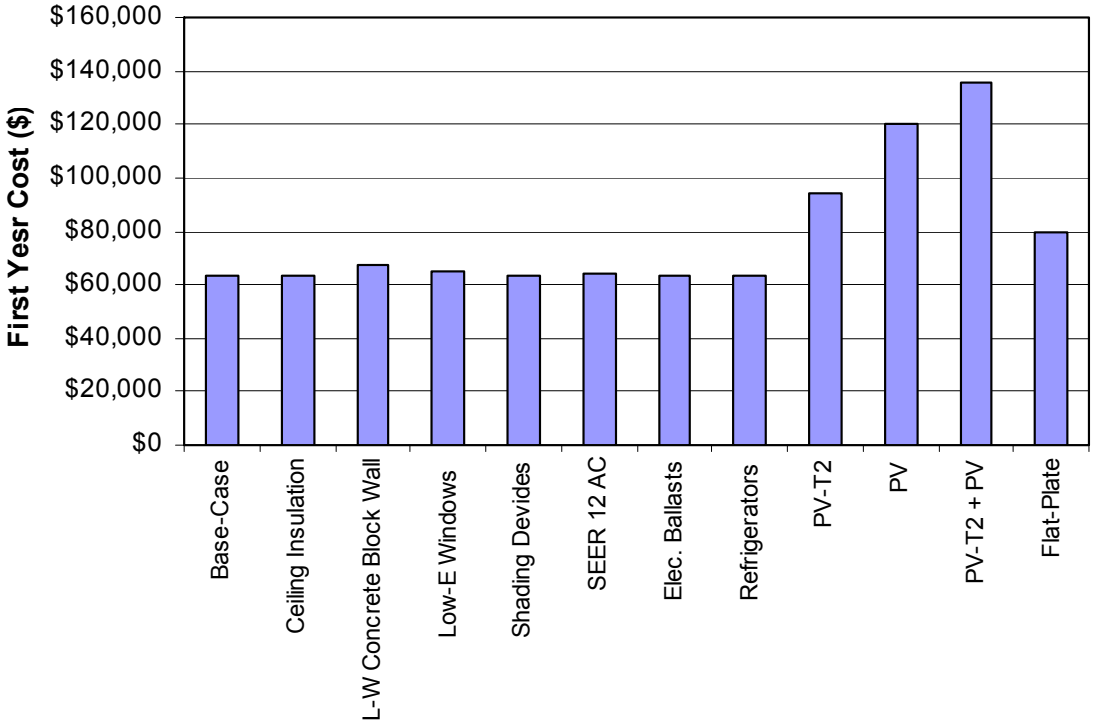


Figure 8.1 *First Year Cost of the Individual Energy Efficiency Strategies and the Renewable Energy Systems.*

In this strategy, the PV arrays were installed on the roof where the space was available after installation of the hybrid PV-T^2 collectors. Installing these two systems on the whole area of the roof was very costly as it can be seen in the Figure 8.1 that the total cost was more than one time of the base-case house.

The maintenance costs of all energy efficiency strategies (except the renewable energy systems) were equal to that of the base case which was $50.00 per year. As can be seen in the Figure 8.2, the total maintenance cost, when the house was equipped with the renewable energy

systems, was considerably higher than those of the base case and the energy efficiency strategies. The annual maintenance cost for either the hybrid PV-T^2 collector system, PV system was $100, while the cost of $150 was estimated for the combination of the two systems. The annual maintenance cost for the Flat-Plate solar collector system was also $100.

The comparison of the annual electricity cost of the base-case house with energy efficiency strategies and renewable energy systems is presented in Figure 8.3. From the figure, the base-case house's annual electricity cost was the highest as compared to those of energy efficiency strategies and renewable energy systems. The annual electricity costs of the house when it was equipped with the Low-e windows and the shading devices were approximately equal to that of the base-case house. The annual electricity costs of the house, when it was

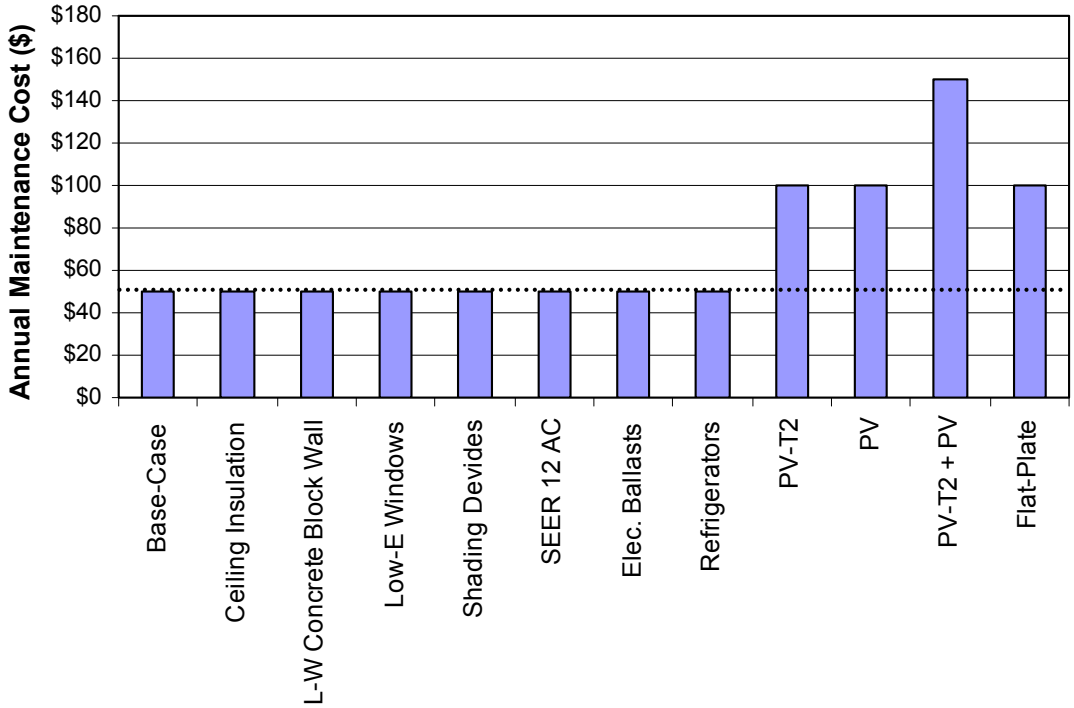


Figure 8.2 *Maintenance Cost of the Individual Energy Efficiency Strategies and the Renewable Energy Systems.*

equipped with the additional insulation on the second floor's ceiling and the electronic ballasts, were slightly lower (approximately 1 percent) lower than that of the base-case house ($4.10 and $3.40 lower, respectively). The SEER-12 air conditioning systems reduced the annual electricity cost by $14.00 (3.6 percent). The insulated light-weight concrete block walls and the new refrigerators were the most effective in the reduction of the electricity cost. The annual electricity cost of the electricity was reduced by $36.00 and $30.00 when the house was constructed with the insulated light-weight concrete block walls and when the new refrigerators were installed.

The renewable energy systems significantly reduced the electricity cost as can be seen the Figure 8.3. The hybrid PV-T^2 collector system and PV system could lower the electricity cost from $396 to $225 (43.25 percent decrease) and $304 (23.30 percent decrease) respectively. The hybrid PV-T^2 collector system was able to reduce more electricity cost, as compared to the PV system, because it could supply all DHW need for the base case as discussed in Chapter VII. Thus a considerably amount of electricity was saved from heating the water by the water heater. The combination of the hybrid PV-T^2 collector system and the PV system resulted in further reduction in the annual electricity cost which was $192. This was approximately 51 percent reduction of the annual electricity cost, which was the highest reduction among the renewable energy systems. The Flat-Plate solar collector system could lower the electricity cost from $396 to $290 (27 percent decrease). This reduction was solely from the supplement of all DHW demand in the house.

The annualized life-cycle cost of the base-case house as compared to the energy efficiency strategies and the renewable energy systems was presented in Figure 8.4. In general, the life-cycle costs of all energy efficiency strategies (except the renewable energy systems) were not significantly different from that of the base-case house. The highest annualized life-cycle cost of the energy efficiency strategies was the light-weight concrete block walls which as -$3,664. This was a difference of $151 as compared to the base case. The lowest annualized life-cycle cost of all strategies was the replacement of the existing refrigerators with the new high energy efficient refrigerators which was $3,481 which was $32.00 lower than that of the base-case house.

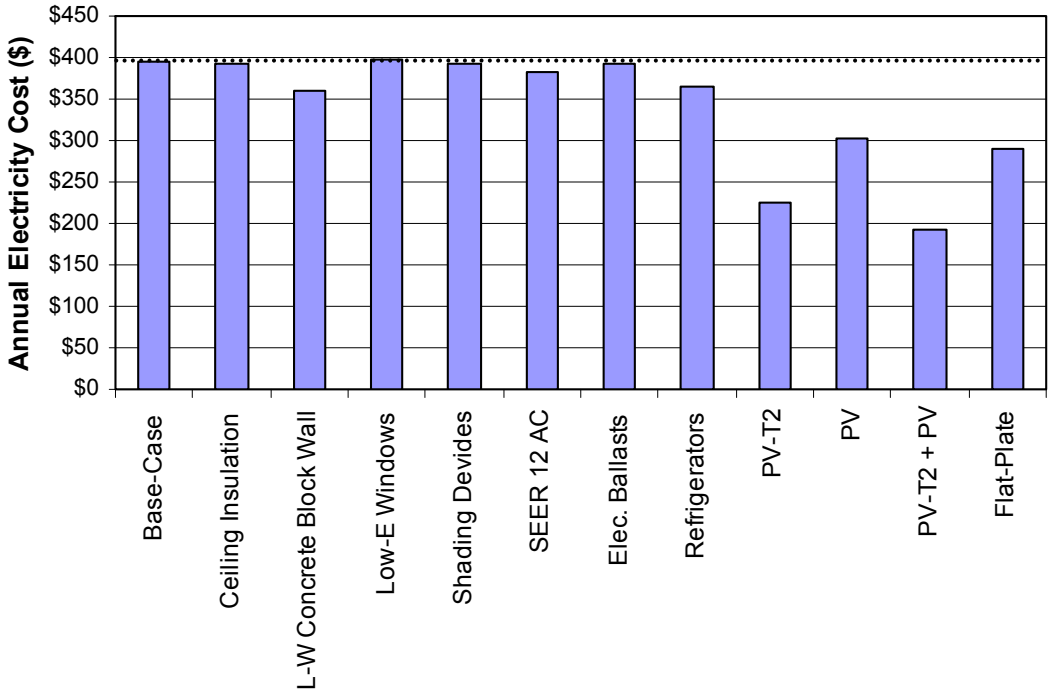


Figure 8.3 *Annual Electricity Cost of the Individual Energy Efficiency Strategies and the Renewable Energy Systems.*

The annualized life-cycle costs of the renewable energy technologies were significantly higher than those of the base-case house and the energy efficiency strategies as shown in Figure 8.4. Among the renewable energy systems, the Flat-Plate solar collector system yielded the lowest annualized life-cycle cost (-$4,165) which is approximately 18.5 percent higher than that of the base-case house. The PV system had the annualized life-cycle cost of -$6,070 which is considerably higher than that of the hybrid PV-T^2 collector system ($1,313 higher). The annualized life-cycle cost of the combination of the hybrid PV-T^2 collector system and the PV system was the highest. Its life-cycle cost was -$1,978 and -$665 more than those of the hybrid PV-T^2 collector systems and the PV systems.

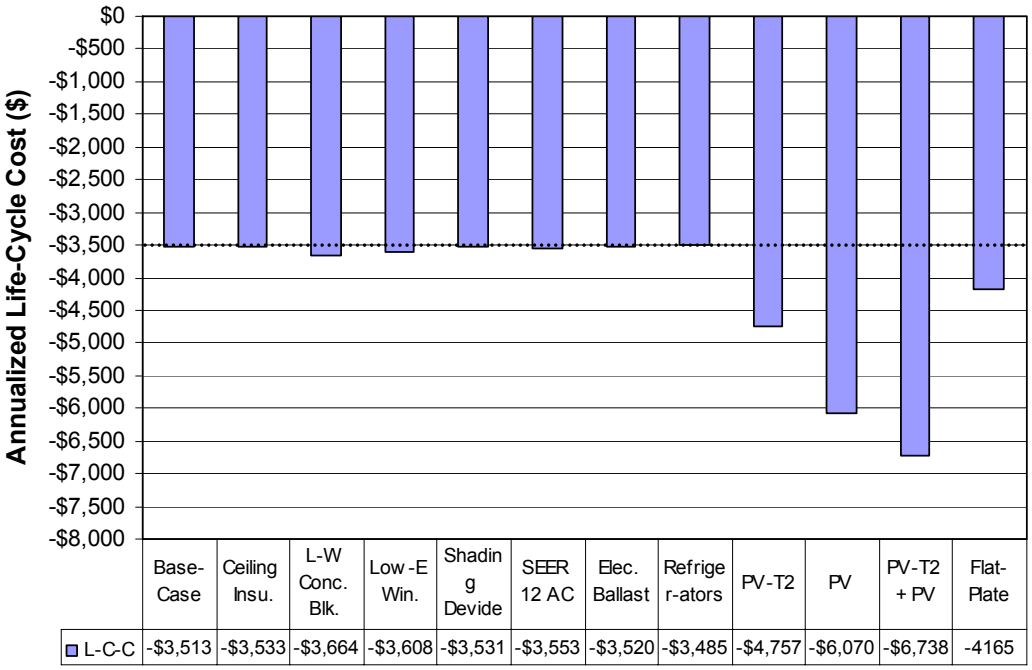


Figure 8.4 *Annualized Life-Cycle Cost of the Individual Energy Efficiency Strategies and the Renewable Energy Systems.*

8.4 Discussion of the Results of the Life-Cycle Cost Analysis of the Combined Energy Efficiency Strategies, and the Renewable Energy Systems

This section discusses the results of the life-cycle cost analysis of Combinations A to G. Combinations A to D were the combined energy efficiency strategies. Combinations E to G were the Combination D with the renewable energy systems. Table 8.4 shows the increased cost of each combination and their total first cost as compared to the base-case's first cost. The maintenance and replacement costs of each combination are presented in Appendix G. The first costs, maintenance and replacement costs of each combination are the following.

Table 8.4

Summary of the Total First Year Cost of the Combined Energy Efficiency Strategies and Renewable Energy Systems

Combinations of Energy Efficiency Strategies and Renewable Energy Technology	Increased Cost	Total First Year Cost
Base-Case House		$63,163
Combination A	$5,981	$69,145
Combination B	$8,080	$71,243
Combination C	$6,438	$69,602
Combination D	$8,537	$71,700
Combination E	$39,530	$102,694
Combination F	$65,676	$128,839
Combination G	$80,695	$143,858

8.4.1 Combination A

Combination A is a strategy that combines Strategies 2, 3-4, 7, 8, and 9 together (see Section 8.2 for the list of strategies). The increased cost of Combination A from the base-case house was $5,981 which resulted in the total first cost of $69,115. The annual maintenance and replacement costs of Combination A were similar to those of the base-case house which was $70 (see Table 8.3). The replacement cost at the 15th year will be $2032. Of this amount, $1,874 will be for the air conditioning systems and $258 will be for electronic ballasts. At the 20th year, the refrigerators will be replaced with the new ones which will cost $750. The annual electricity cost of Combination A was $312 which was $84 lower than that of the base-case. The annualized life-cycle cost of Combination A was -$3,711 which was an increase of $198 from the annualized life-cycle cost of the base-case house.

8.4.2 Combination B

Combination B is a strategy that combines Combination A with Strategy 4 (low-e glass). The increased cost of Combination B from the base-case house was $8,080 which resulted in the total first cost of $71,243. The annual maintenance and replacement costs of Combination B were identical to Combination A. The replacement costs at the 15th and 20th year were also the same with Combination A. The annual electricity cost of the Combination B was $310 which was $85 lower than that of the base-case. The annualized life-cycle cost of

Combination B was -$3,804 which was an increase of $291 from the annualized life-cycle cost of the base-case house.

8.4.3 Combination C

Combination C is a strategy that combines Combination A with Strategy 5 (shading devices). The increased cost of Combination C from the base-case house was $6,439 which resulted in the total first cost of $69,602. The annual maintenance and replacement costs of Combination C were identical to Combinations A and B. Since there was no replacement required for the shading devices, the replacement costs at the 15th and 20th year were also the same with Combinations A. The annual electricity cost of the Combination C was $311 which was $84 lower than that of the base-case. The annualized life-cycle cost of Combination C was -$3,732 which was an increase of $219 from the annualized life-cycle cost of the base-case house.

8.4.4 Combination D

Combination D is a strategy that combines Combination A with Strategy 4 (low-e glass) and Strategy 5 (shading device). The increased cost of Combination D from the base-case house was $8,537 which resulted in the total first cost of $71,700. The annual maintenance and replacement costs of Combination D were identical to Combinations A, B and C. The replacement costs at the 15th and 20th year were also the same with Combinations A, B and C. The annual electricity cost of Combination D was $310 which was $86 lower than that of the base case. The annualized life-cycle cost of Combination D was -$3,824 which was an increase of $311 from the annualized life-cycle cost of the base-case house.

8.4.5 Combination E

Combination E combines Combination D with Renewable Energy Technology 1 (i.e., hybrid PV-T^2 collector system). The increased cost of Combination E from the base-case house was $39,530 which resulted in the total first cost of $102,694. The annual maintenance and replacement costs of Combination E were $120 which increased by $50 from those of Combination D due to the maintenance cost of the hybrid PV-T^2 collector system. The annual electricity cost of Combination E was $139 which was $257 lower than that of the base-case.

The annualized life-cycle cost of Combination E was -$5,069 which was an increase of $1,556 from the annualized life-cycle cost of the base-case house.

8.4.6 Combination F

Combination F combines Combination D with Renewable Energy Technology 2 (PV system). The increased cost of Combination F from the base-case house was $65,676 which resulted in the total first cost of $128,839. The annual maintenance and replacement costs of Combination F were $120, which increased by $50 from those of Combination D due to the maintenance cost of the PV system. The annual electricity cost of Combination F was $232 which was $164 lower than that of the base-case. The annualized life-cycle cost of Combination F was -$6,420 which was an increase of $2,907 from the annualized life-cycle cost of the base-case house.

8.4.7 Combination G

Combination G combines Combination D with Renewable Energy Technology 3 (hybrid PV-T^2 collector system and PV system). The increased cost of Combination G from the base-case house was $80,695 which resulted in the total first cost of $143,858 The annual maintenance and replacement costs of Combination F were $170 which increased by $100 from those of Combination D due to the maintenance cost of the hybrid PV-T^2 collector system and the PV system. The annual electricity cost of Combination G was $109 which was $287 lower than that of the base-case. The annualized life-cycle cost of Combination F was -$7,724 which was an increase of $4,211 from the annualized life-cycle cost of the base-case house.

8.5 Comparisons of the Results of the Life-Cycle Cost Analysis of the Combined Energy Efficiency Strategies and Renewable Energy Systems

This section compares the results of the life-cycle cost analysis of the base-case house with Combinations A to G. Figure 8.5 presents the first cost of the base-case house as compared to those of the Combinations A to G. From Figure 8.5, the first costs of Combinations A to D were higher than the base case; the increased costs were in a range of $6,000 to $8,500 from that of the base case. The first costs of Combination E to G were considerably higher than that of the base case and Combinations A to D. As can be seen in

Figure 8.5, the increased costs of Combination A to D were much lower than that of Combination E to G which combined the renewable energy systems with the energy efficiency strategies.

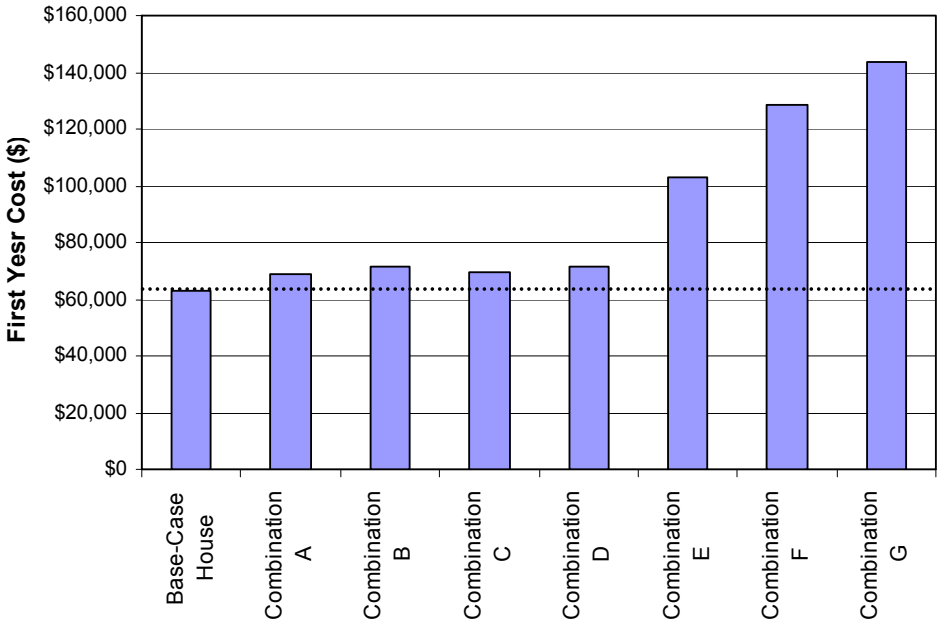


Figure 8.5 *First Year Cost of the Combined Energy Efficiency Strategies and the Renewable Energy Systems.*

Figure 8.6 present the annual maintenance cost of the base-case house as compared to those of Combination A to G. The annual maintenance costs of Combinations A to D were $50 which equaled to that of the base-case house. The annual maintenance costs of Combinations E and F were $100. The annual maintenance cost of Combination G was the highest among all combinations which was $150.

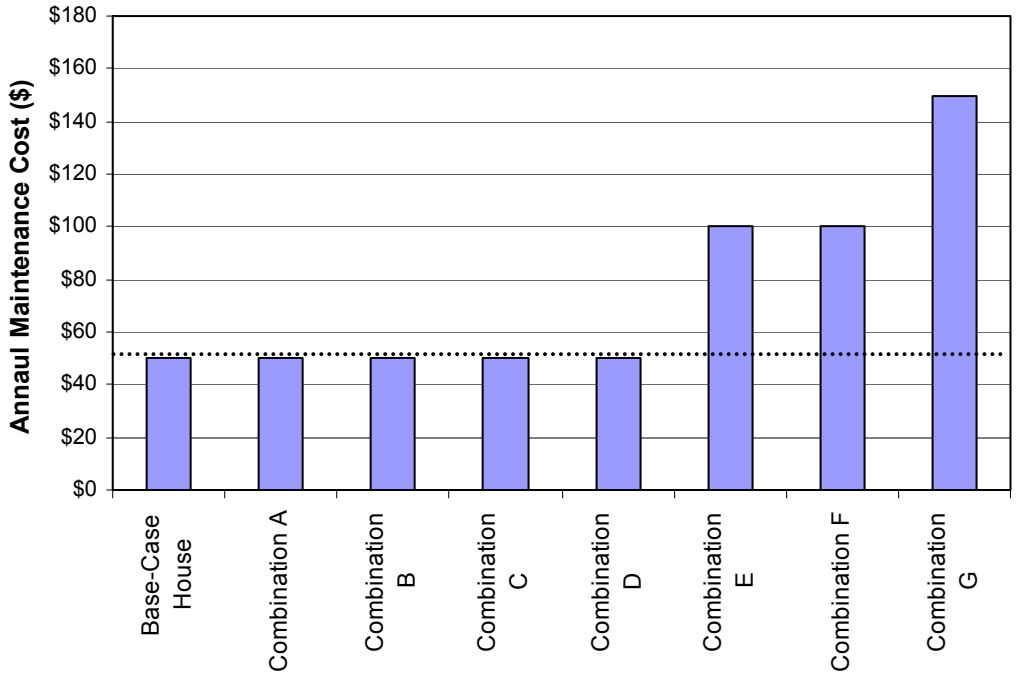


Figure 8.6 *Annual Maintenance Cost of the Combined Energy Efficiency Strategies and the Renewable Energy Systems.*

The annual electricity costs of Combinations A to G are compared with that of the base case as shown in Figure 8.7. From the figure, the annual electricity cost of Combinations A to D were approximately $310 which approximately $85 lowered than the base-case's annual electricity cost. The annual electricity costs of Combination E to G were significantly lower than that of the base-case. Combination E, which equipped the hybrid PV-T^2 collector system with Combination D, ranked the second lowest annual electricity cost ($139) as compared to Combinations A to G. Combination F, which equipped the PV system with Combination D, ranked the third lowest annual electricity cost ($232) as compared to Combinations A to G. Combination G reduced the base-case's annual electricity cost to $108 which was the lowest annual electricity cost as compared to all combinations.

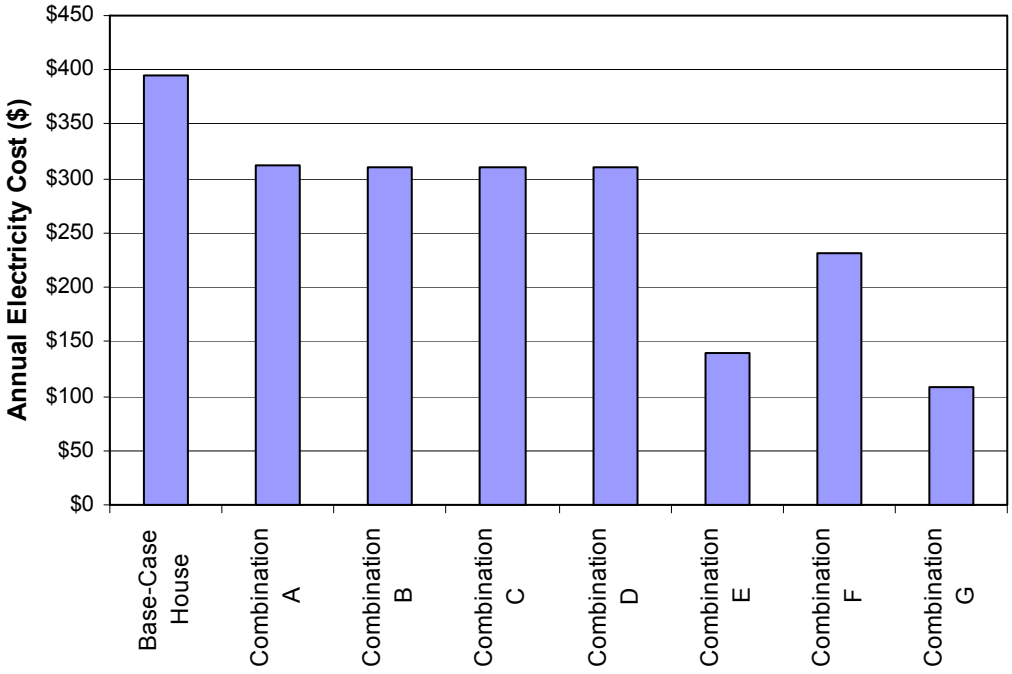


Figure 8.7 *Annual Electricity Cost of the Combined Energy Efficiency Strategies and the Renewable Energy Systems.*

The results of the annualized life-cycle cost of the base-case as compared to Combinations A to G are shown in Figure 8.8. From the figure, it can be seen that the annualized life-cycle cost of the base case were the lowest. The annualized life-cycle costs of all combinations were higher than that of the base case. However, the annualized life-cycle costs of Combinations A to D were relatively close to that of the base case, while the annualized life-cycle costs of Combination E to G were significantly higher than the base case's annualized life-cycle cost. Combination G had the annualized life-cycle cost of $7,006 which was two times higher than that of the base case. However, annual operating costs of a house with the PV-T^2 system would be much less affected by rising energy costs.

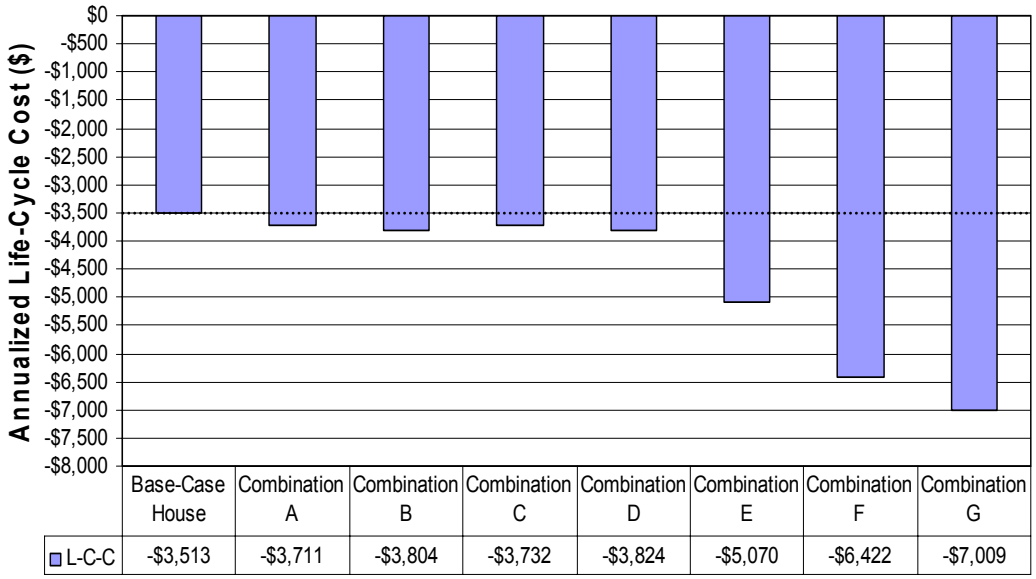
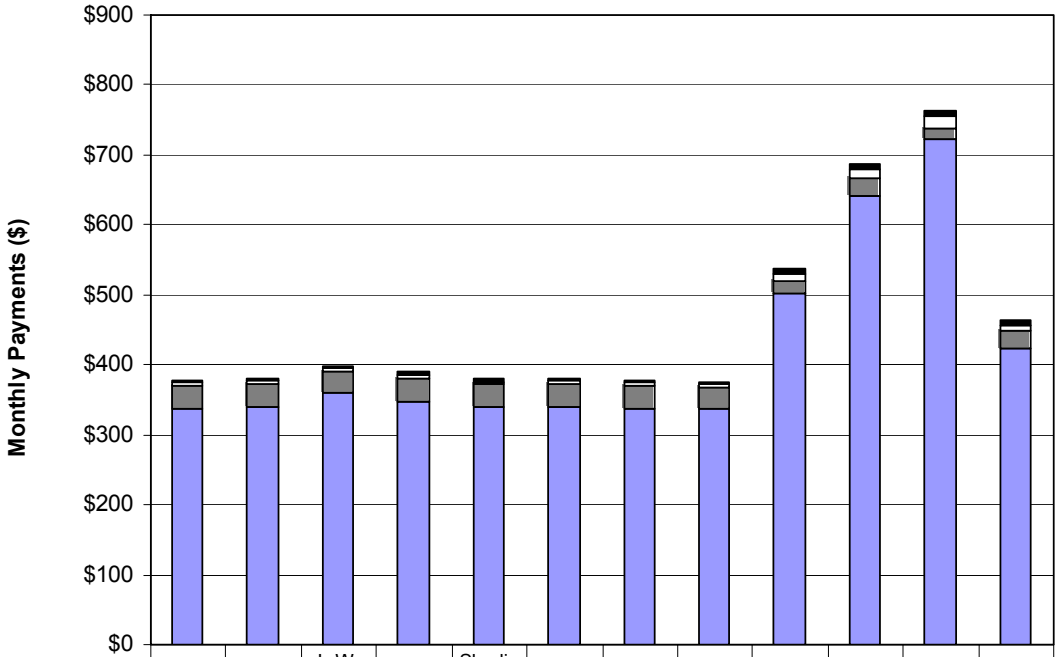


Figure 8.8 *Annualized Life-Cycle Cost of the Combined Energy Efficiency Strategies and the Renewable Energy Systems.*

8.6 Analysis of the Monthly Payments on the Case-Study House

Figure 8.9 shows the average monthly payments of the base-case house as compared to the individual energy efficiency strategies. The monthly payment consists of insurance cost, maintenance costs, electricity costs and mortgage costs. In Figure 8.9, the mortgage cost is the largest portion of the monthly payment. All of the monthly payments were close to the base-case's monthly payment except those of renewable energy systems. The base-case monthly payment was $337, while the energy efficiency strategies' monthly payments were in a range of $340 to $722. The monthly payments of hybrid PV-T^2 collector system, PV system and their combination were considerably high as compared to those of the base case and the energy efficiency strategies, which was due to the high cost of mortgage payment. The electricity costs were dramatically reduced by that renewable energy systems, however, the electricity costs were relatively small portions of the monthly payments. Thus, the reduction in the electricity cost due to the implementation of the renewable energy systems had little effect on the monthly payments. Among the renewable energy systems, the monthly payment of the Flat-Plate solar

collector system was the lowest ($424), which was an increase of approximately 25 percent from the base-case.

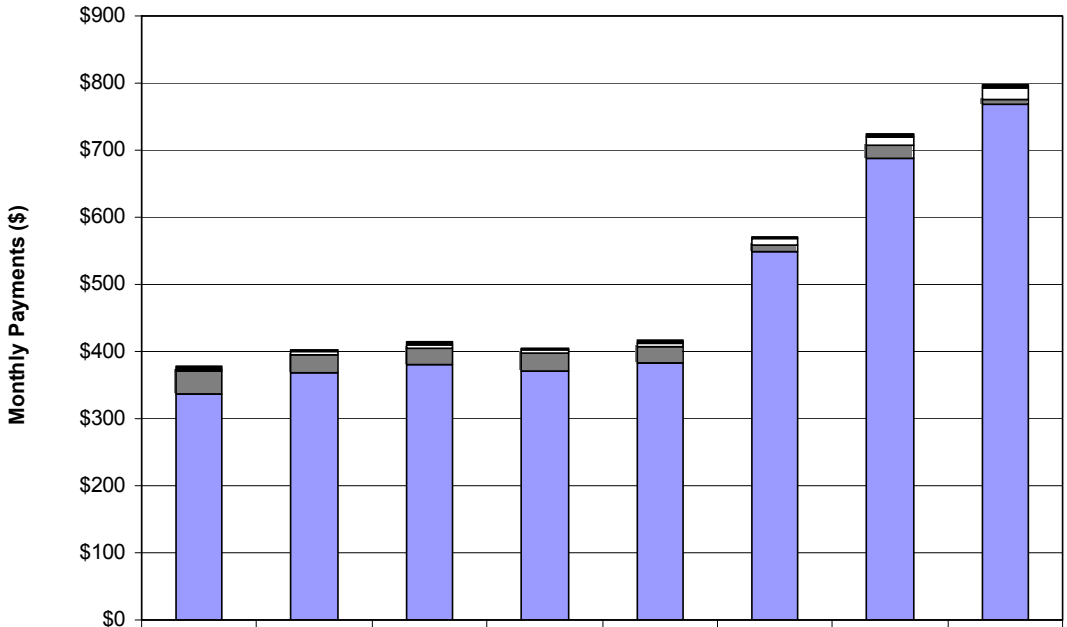


	Base-Case	Ceiling Insu.	L-W Conc. Blk.	Low-E Win.	Shading Devide	SEER 12 AC	Elec. Ballast	Refrigerators	PV-T2	PV	PV-T2 + PV	Flat-Plate
Insurance Cost	$4.2	$4.2	$4.2	$4.2	$4.2	$4.2	$4.2	$4.2	$8.3	$8.3	$8.3	$8.3
Maintenance Cost	$4.2	$4.2	$4.2	$4.2	$4.2	$4.2	$4.2	$4.2	$8.3	$12.5	$16.7	$8.3
Electricity Cost	$33.0	$32.6	$30.0	$33.0	$32.8	$31.8	$32.7	$30.4	$18.7	$25.3	$16.0	$24.2
Mortgage	$336.9	$339.9	$360.2	$348.1	$339.4	$340.9	$337.9	$337.6	$502.3	$641.7	$721.9	$423.5

Figure 8.9 *Monthly Payments of the Case-Study House for the Individual Energy Efficiency Strategies and the Renewable Energy Systems.*

Figure 8.10 shows the average monthly payments of the base-case house as compared to Combinations A to G. The monthly payments shown in Figure 8.10 were similar to those in Figure 8.9. The monthly payments of Combinations A to D, which combined energy efficiency strategies together, were relatively close to the base-case monthly payment. The base-case

monthly payment was $337, while monthly payments of Combination A to D were in a range of $369 to $382. The monthly payments of Combinations E to G were relatively high, which was due to the high mortgage payments. Combinations E to G combined energy efficiency strategies with renewable energy systems, which have high first costs. This caused considerably high monthly payments although the monthly electricity costs were significantly reduced.



	Base-Case House	Combination A	Combination B	Combination C	Combination D	Combination E	Combination F	Combination G
Insurance Cost	$4.17	$4.17	$4.17	$4.17	$4.17	$4.17	$4.17	$4.17
Maintenance Cost	$4.17	$4.17	$4.17	$4.17	$4.17	$8.33	$12.50	$16.67
Electricity Cost	$32.97	$25.97	$25.85	$25.94	$25.82	$11.57	$19.34	$9.04
Mortgage	$336.93	$368.84	$380.03	$371.28	$382.47	$547.80	$687.27	$767.39

Figure 8.10 *Monthly Payments of the Case-Study House for the Combined Energy Efficiency Strategies and the Renewable Energy Systems.*

8.7 Summary and Conclusion

This chapter discussed the economic analysis of the case-study house as compared with the building that was improved by the energy efficiency strategies and the renewable energy technologies. The first cost, maintenance and replacement costs, and energy costs were presented for each scenario. The final results of the economic analysis, which were annualized

life-cycle costs and monthly payments, were then presented and discussed. The results from the analysis showed that the lowest annualized life-cycle cost ($3,481) was achieved by Strategy 9, which was the replacement of new refrigerators. This strategy did not only yield the lowest annualized life-cycle cost, but it was also the only strategy that had an annualized life-cycle cost was that lower than the base case.

The results of monthly payments of the energy efficiency strategies including Combinations A to D showed that their monthly payments were not significantly higher than that of the base-case house. This suggested that improving the base-case house using the energy efficiency strategies for Combination A to D (except renewable energy systems) should be acceptable to consumers if an emphasis is placed on annual operating costs, versus first costs. Strategies E, F and G would need significant mortgage incentives to make them affordable by an average homeowner. On the other hand, if energy prices increase significantly beyond current prices (i.e., 2 to 3 times today's costs) this would significantly change the assumption used in the economic analysis, resulting in more emphasis in reducing energy use.

CHAPTER IX

SUMMARY AND RECOMMENDATIONS

This chapter presents the summary of the results from previous chapters and proposes a recommendation or a guideline for improving residential buildings in hot humid climates and recommendations for future research. Section 9.1 summarizes the results of the case-study house, hybrid PV-T^2 experiments and building energy simulations that were presented in the previous chapters. A guideline for improving energy efficiency and thermal comfort in Thai residential buildings was discussed in Section 9.2. Section 9.3 discusses future work that could be further investigated in the fields of hybrid PV-T^2 collector system and energy efficiency in Thai residential buildings.

9.1 Summary of Results

Thermal conditions and building energy use in the case-study house were investigated. The thermal conditions in the house were found to be outside the ASHRAE comfort zone. Although this research considers that a Thais' thermal comfort may be different from as specified in the ASHRAE comfort zone, occupants were expected to live under condition that were not thermally comfortable (i.e., high temperature and high humidity conditions), which occurred mostly in unconditioned spaces (i.e. living room, and bedroom-3) and in the master bedroom in the daytime. Energy consumption of the case-study house was found to be above the average energy consumption of a Thai detached house. This was felt to be due to the number of appliances (i.e., two refrigerators and two air conditioning systems) were more than an average household contained.

The thermal, electrical, and heat rejection performances of the hybrid PV-T^2 collector system were tested and discussed. The hybrid PV- T^2 collector system had the maximum thermal efficiency of 45 percent. The measured Test Intercept ($Fr\tau\alpha$) was 0.45 and the measured collector loss coefficient data was -5.6194, which represent FrUL. Thermal efficiency of the hybrid PV-T^2 collector system varied significantly with ambient temperature, the thermal efficiency becoming zero at $(t_i - t_a)/I_t > 0.08$, which approximately corresponds to an inlet temperature of 88 ºF, under bright solar condition of 300 Btu/ft^2·h and an ambient

temperature of 68 ºF. The relationship of the PV-T^2 panel's electrical efficiency and panel temperature was reported. The electrical efficiency decreases at the rate of 0.0005 percent per one degree Celsius. This value was the array temperature coefficient of the hybrid PV- T^2 collector, which was later used for the system input parameter in the PV F-Chart program to analyze the electrical performance of the Hybrid PV- T^2 system. The total efficiency, which is the combined thermal and electrical efficiencies, was found from the day mode experiment. The maximum total efficiency [when $(t_i-t_a)/I_t = 0$] was approximately 54 percent.

The experimental results, which tested the heat rejection for the whole system (tank + pump), were presented and compared with the theoretical results. The theoretical heat rejection rates were much lower than that of the experimental results. From the experimental results, relationships between heat rejection rates and three variables [i.e., wind speed, $T_{sur} - T_a$, and $(T_{sur4} - T_{sky4})* \delta$] were found. A linearized regression analysis of the relationships between the experimental heat rejection rates and those variables was performed and reported. A regression analysis of the relationships between the water temperature in the tank and those variables was also performed and reported.

The results of building simulation using the DOE-2 program, combined with the results from F-Chart and PV-T Chart programs were reported. For the individual energy efficiency strategies (excluding the renewable energy systems), Strategy 3-4 (insulated light-weight concrete block walls) was the most effective strategies (9.08 percent of total energy reduction). Strategies 3-2, 3-3, and 3-4 were also effective (4th, 3rd, 2nd, respectively).

When comparing the results of all individual strategies including the renewable energy systems (Strategies 1 to 13), Strategy 13 (Renewable Energy Technology 3: hybrid PV-T^2 system and PV system) was ranked in 1st. It reduced the base-case energy use by 51 percent. The individual PV-T^2 collector system (Strategy 10) and the flat-plate solar collector system (Strategy 14) were ranked second and third, respectively (a reduction of 43.25 percent and 26.71 percent of the building's energy use, respectively). The PV system was ranked in the forth place, which reduced energy use by 23.30 percent). It is interesting that the flat-plate solar collector system, could reduce energy use more the PV system. This is certainly because the flat-plate solar collector system could supply all DHW needs, which is highest energy use in all categories, while the PV system, which had no battery storage, could not supply electricity to the DHW system since the DHW was used in the early morning and evening.

The results of Combination A to G which were shown in Table 7.32, Combination G was ranked in 1st place which was able to reduce the building's energy use by 72.58 percent. Combination E and F were ranked in the 2nd and 3rd (64.92 and 41.35 percent, respectively). From these analyses, it is clear that achieving a zero net energy house would only require a modest investment over Combination G.

An annualized life-cycle cost analysis of the case-study house, energy efficiency strategies and the renewable energy technologies was preformed. The results from the analysis showed that the lowest annualized life-cycle cost ($3,481) was achieved by Strategy 9 which was the replacement of new refrigerators. This strategy did not only yield the lowest annualized life-cycle cost, but it was also the only strategy that had an annualized life-cycle cost was that lower than the base-case. The results of monthly payments of the energy efficiency strategies including Combinations A to D showed that their monthly payments were not significantly higher than that of the base-case house. This suggested that improving the base-case house using the energy efficiency strategies shown (except renewable energy systems) should be acceptable to consumers if an emphasis is placed on annual operating costs, versus first costs.

9.2 Recommendation for Improving Residential Buildings in Hot and Humid Climates

As described in the research objective, this research aimed to develop generalized design and housing characteristics in term of energy conservation and affordability for hot-humid climates.

The generalized design for energy conservation alone may not totally be applicable in residential buildings in hot-humid climates. Although the case-study house represented a typical Thai residential building in a hot-humid climate, differences in occupants' lifestyles may need different solutions or strategies. In addition, the economic scenarios that were used in the life-cycle cost analysis used a Thailand's economic input variables. Thus, the recommendations that were based on the financial feasibility from the life-cycle cost analysis are only appropriate for Thailand's circumstances. Hence, they may not be applicable or appropriate for residential buildings in other hot-humid climate regions that have different economic conditions. The recommendations are discussed below.

1) From the results of the economic analysis, Strategy 9 (high energy efficient refrigerators) had the lowest annualized life-cycle cost as compared to the base-case house, all energy efficiency

strategies, renewable energy systems, and Combinations A to G. The replacement of the refrigerators is also the simplest strategy that could be accomplished by occupants or homeowners. Thus, this strategy is the first recommendation in the improvement of the building. However, although high energy efficient refrigerators could significantly reduce building energy use, they did not significantly improve the simulated space temperatures.

2) From the simulation results of Strategy 5 (Shading devices), simulated temperatures in the living spaces slightly decrease after shading devices were installed (see Figure 7.30). Although the shading devices may not dramatically improve the thermal conditions in the living spaces, a slightly decrease in space temperature is considered as a major improvement of the spaces' thermal conditions since the base case's space temperatures were considered uncomfortable as discussed in Chapter V. Therefore shading devices especially for south facing rooms are recommended.

3) Similar to Strategy 5, the results of Strategy 4 (low-e windows) showed that daytime space temperatures slightly decreased after installing the low-e windows. Thus, for the room that is occupied or the room that has an air-condition system operated in the daytime, low-e windows would be effective for improving of the room's thermal condition and results in small reduction of energy used by the air conditioning system.

However, in the case of the case-study house, the master bedroom and bedroom-3 were only the spaces that were air-conditioned and they were operated only during the nighttime. Hence, the low-e windows and shading had a limited impact on reducing the energy use. Also as mentioned in Chapter VII, Section 7.3.4, during the nighttime, there were periods of time where the ambient temperatures were lower than the room temperatures of the conditioned spaces. In this situation, low-e windows transmitted less heat to the environment as compared to the single-pane windows. Thus, there was an unexpected higher cooling load on the air conditioning system when the low-e windows were used. Fortunately, this only caused an increase of 0.2 percent of the energy consumed by the air conditioning systems. Therefore, installing low-e windows in the nighttime air-conditioned spaces does not significantly reduce energy used by the air conditioning systems. Because of this, the low-e windows are not recommended in the nighttime air-conditioned spaces, but they are recommended for daytime air-conditioned spaces.

4) For the improvements to the building systems, SEER-12 air conditioning systems and electronic ballasts were cost effective; from the results of economic analysis, annualized life-cycle costs and monthly payments of both were very close to those of the base-case house. Therefore, SEER-12 air conditioning systems and electronic ballasts are recommended.

5) Strategy 3-4 (insulated light-weight concrete block walls) was the most effective strategy in the reduction of building energy use. However, insulated light-weight concrete block walls were not cost effective due to their relatively high cost as compared to the typical four-inch brick walls. However, in the study of building simulation of Strategy 3-4, all four-inch brick exterior walls were replaced by the insulated light-weight concrete block walls. Nevertheless, the building energy use was decreased due to the air conditioning systems that operated in only 2 rooms (i.e. mater bedroom and bedroom-3). Thus replacement of the existing exterior walls with the insulated light-weight concrete block walls for the air-conditioned spaces certainly would cost much less than replacement of the whole exterior walls of the building. This strategy was not simulated because energy reductions due to the replacement of the exterior walls of the air-conditioned spaces were expected not to be significantly different from the energy reduction results of the Strategy 3-4. Hence, the Economic analysis of the selectively improved exterior walls needs to be further studied.

6) The results of monthly payments of the energy efficiency strategies, which include second floor ceiling insulation, insulated light-weight concrete block walls, shading devices, SEER-12 air conditioning systems, electronic ballasts, high efficiency refrigerators, and Combinations A to D, showed that their monthly payments were not significantly higher than that of the base-case house. Thus, improving the base-case house using these energy efficiency strategies is recommended

In summary, all individual strategies analyzed in the economic analysis except Strategies 10 to 12 and Combination A to D are recommended. Low-e windows are recommended for daytime air-conditioned spaces. Insulated light-weight concrete block walls are recommended for air-conditioned spaces.

9.3 Recommendations for Future Research

1) Applications of Heat Rejection by the hybrid PV-T^2 Collectors

The results from the night mode experiment showed that heat could be rejected from the PV panel by the means of radiative and convective heat losses. However, the impact of this strategy's cooling performance or heat removing capacity on the case-study house was not simulated with the DOE-2 programs. PV panels that are used to reject heat could provide a significant improvement for situation where a significant amount of 120 ºF heat needs rejecting. One example might be the use of a "cool" storage reservoir that is cooled each night and then used the following day to reduce condenser temperatures. This would improve the efficiency of the air conditioning systems. Therefore, this needs further study.

2) Study of Indoor Air Quality (IAQ) in Thai Residential Building

In the study of case-study house, it was found that relative humidities in the living spaces were significantly high. There were many times that relative humidities in the master bedroom and the living room were higher than 70 percent which can indicate the beginning of mold and mildew. However, when the case-study house's survey was preformed, there were no appearance of mold and mildew on the interior surfaces of the walls. Mold may not be visible or it may not be present on the surfaces (such as walls) in the space. This may be due to the fact that growth of mold requires sufficient time at specific thermal conditions (temperature and humidity). ASHRAE (1999, p 20.2) presents the time required for visible mold growth. For instance, at 70 percent relative humidity, visible mold growth requires approximately 100 days (at 77 ºF). Although temperatures in the living space were mostly above 77 ºF (see Figure 5.15), the relative humidity was not high all the time. Thus this may explain the lack of visible mold in the case-study house. However, this research was not aimed to study IAQ problems in Thai residences, but rather studies the general characteristics of thermal conditions in Thai residential buildings. Further study of mold growth in Thai residential buildings or in partially-conditioned residential buildings in hot and humid climates are essential to improve the building's IAQ.

3) Applications of Excess heat from the hybrid PV-T^2 Collectors

From the discussion about further study in IAQ of Thai residential building in previous section, there is a recommendation on an application of the thermal energy (warm water) that is

produced by the hybrid PV-T^2 Collectors. The available warm water which may exceed the DHW demand may be used to dehumidify the humid indoor air. To accomplish this, a concentrated salt solution is sprayed into the air stream to absorb moisture from the indoor air. As this salt solution absorbs moisture it becomes a weak salt solution. This weak salt solution is then reconcentrated by evaporating the water at 180-212 ºF using heat from the solar collectors. This strong salt solution is then cooled and recirculated back to the spray chamber where it absorbs moisture etc. Such a system is capable of removing a large portion of the moisture, which will reduce indoor humidity level and improve comfort conditions. Also, since it obtains its heat from the solar collectors it accomplishes this dehumidification at a fraction of the electricity used in a normal A/C system.

REFERENCES

American Society of Heating, Refrigerating and Air Conditioning Engineers (ASHRAE) 1989. *ASHRAE Standard 96-1980 (RA 1989)*, ASHRAE Inc., Atlanta, GA.

American Society of Heating, Refrigerating and Air Conditioning Engineers (ASHRAE) 1992. *ANSI/ASHRAE Standard 55-1992*, ASHRAE Inc., Atlanta, GA.

American Society of Heating, Refrigerating and Air Conditioning Engineers (ASHRAE) 1995. *ANSI/ASHRAE Standard 55a-1995 (Addendum to ANSI/ASHRAE 55-1992)*, ASHRAE Inc., Atlanta, GA.

American Society of Heating, Refrigerating and Air Conditioning Engineers (ASHRAE) 1999. *1999 ASHRAE Handbook HVAC Applications*, ASHRAE Inc., Atlanta, GA.

American Society of Heating, Refrigerating and Air Conditioning Engineers (ASHRAE) 2001 *2001 ASHRAE Handbook Fundamentals*, ASHRAE Inc., Atlanta, GA.

American Society for Testing and Materials (ASTM) 1996. *ASTM Standard E 1036-96: Standard Test Methods for Electrical Performance of Nonconcentrator Terrestrial Photovoltaic Modules and Arrays Using Reference Cell*, ASTM, West Conshohocken, PA.

American Society for Testing and Materials (ASTM) 1997. *ASTM Standard E 563-97: Standard Practice for Preparation and Use of an Ice-Point Bath as a Reference Temperature*, ASTM, West Conshohocken, PA.

Ander, G. O. 1995. *Daylighting Performance and Design,* Van Nostrand Reinhold, New York, NY.

Bank of Thailand (BOT). 2004. *Inflation Report January 2004*, Bangkok, Thailand.

Berdahl, P. and Martin, M. 1984. Emissivity of Clear Sky, *Solar Energy* 32(5).

Bergene, T. and Løvvik, O. M. 1995. Model Calculations on a Flat-plate Solar Heat Collector with Integrated Solar Cells, *Solar Energy* 55(6), 453-462.

Berglund, L. G. 1998. Comfort and Humidity*, ASHRAE Journal*, August, 35-41.

Blast Support Office (BSO) 1993. *Blast User Reference*, Department of Mechanical and Industrial Engineering, University of Illinois at Urbana-Champaign, Urbana-Champaign, IL.

Brinkworth, B.J., Cross, B.M., Marshall, R.H. and Hongxing, Y. 1997. Thermal Regulation of Photovoltaic Cladding. *Solar Energy* 61(3), 169-178.

Boonyatikarn, S. 1999 *Technique of Designing Energy Saving House for Better Quality Life*, Chulalongkorn University Press, Thailand.

Bou-Saada, T. E. 1994. *An Improved Procedure for Developing Calibrated Hourly Simulation Models of an Electrically Heated and Cooled Commercial Building*. M.S. Thesis, Texas A&M University, College Station, Texas.

Bou-Saada, T., and J. Haberl. 1995. An Improved Procedure for Developing Calibrated Hourly Simulation Models. *Proceedings of Building Simulation '95* (pp. 99-113). International Building Performance Simulation Association, Madison, WI.

Bronson, D. 1992. *Calibrating DOE-2 to Weather and Non-weather-dependent Loads for a Commercial Building*. Master's thesis, Texas A&M University, College Station.

Bronson, D., S. Hinchey, J. Haberl, and D. O.Neal. 1992. A Procedure for Calibrating the DOE-2 Simulation Program to Non-weather-dependent Measured Loads. *ASHRAE Transactions* 98(1):636-652.

Bureau of Budget. 2004. *2004 Thailand Construction Material and Labors Costs*. Office of Prime Minister, Bangkok, Thailand.

Busch, J. F. 1990. Thermal Response to the Thai Office Environment. *ASHRAE Transactions* 96(1), 859-872.

Campbell Scientific Inc. 1989. *21X Micrologger Operator's Manual*. Campbell Scientific Inc., Logan, UT.

Campbell Scientific Inc. 2001. *PC208W Datalogger Support Software Instruction Manual*. Campbell Scientific Inc., Logan, UT.

Chulsukon, P. 2002. *Development and Analysis of a Sustainable, Low Energy House in a Hot and Humid Climate.* Master's thesis, Texas A&M University, College Station, TX.

Crawley D. B., Lawrie, L.K., Winkelmann, F.C. Buhl, W.F., and Huang Y.J., 2000. EnergyPlus: Creating a New-Generation Building Energy Simulation Program, *Energy and Buildings* 33, 319-331.

Department of Energy Development and Promotion (DEDP) 1998. *Thailand Energy Situation 1998*, Department of Energy Development and Promotion, Ministry of Science, Technology and Environment, Thailand.

Duffie J. A. and Beckman W. A. 1991. *Solar Engineering of Thermal Processes*, Wiley, New York.

Electricity Generation Authority of Thailand (EGAT). 1998. Load Forecast for the Thailand Electric System (Executive Summary), September p.18., Bangkok, Thailand.

Energy Conservation Promotion Fund (ECPF). 2000. Energy Conservation Program and Guidelines, Criteria, Conditions and Expenditure of the Energy Conservation Promotion Fund During the Fiscal Period 2000-2004, National Energy Policy Council (NEPC), Bangkok, Thailand.

Energy Information Administration (EIA). 2003. International Energy Outlook 2003, Energy Information Administration, U.S. Department of Energy, Washington, D.C.

Energy Policy and Planning Office (EPPO) 2001. *Executive Summary of Minimum Efficiency Performance Standards,* Ministry of Energy, Bangkok, Thailand.

Energy Policy and Planning Office (EPPO) 2003. *Table 40: Electricity Consumption for the Whole Country*, Ministry of Energy, Bangkok, Thailand. Retrieved June 23, 2003, from http://www.eppo.go.th/info/ T40.html.

Food and Agriculture Organization of the United Nations (FAO). 1981. *Forest Resources of Tropical Asia*, Food and Agriculture Organization of the United Nations, Rome.

Garg, H. P. and Adhikari, R. S. 1997. Conventional Hybrid Photovoltaic/Thermal (PV/T) Air Heating Collectors: Steady-State Simulation, *Renewable Energy* 11(3), 363-385.

Garg, H. P. and Adhikari, R. S. 1999. System Performance Studies on a Photovoltaic/Thermal (PV/T) Air Heating Collector, *Renewable Energy* 16, 725-730.

Garg, H. P. and Agarwal, R. K. 1995. Some Aspects of a PV/T Collector/Forced Circulation Flat Plate Solar Water Heater with Solar Cells, *Energy Conversion Management* 36(2), 87-99.

GC Electronics. 2003. Chemical Product Specification Sheet (Silicone Type Z9 Heat Sink Compound). Cat. No. 10-8109,GC/Waldom Inc., Rockford, IL.

Greenspan, L. 1976. Humidity Fixed Points of Binary Saturated Aqueous Solutions. *Journal of Research* 81(1), 89-96.

Haberl, J.S. 1988. *Using the DOE-2 Building Energy Analysis Computer Program; Session one*, Joint Center for Energy Management, Department of Civil, Environmental, and Architectural Engineering, University of Colorado, Boulder, CO.

Haberl, J.S., and J. Vajda. 1988. Use of Metered Data Analysis to Improve Building Operation and Maintenance: Early Results from Two Federal Complexes, *Proceedings from the ACEEE 1988 Summer Study on Energy Efficiency in Buildings*, Vol. 3, 3.98-3.111, American Council for an Energy Efficient Economy, Washington , DC.

Haberl, J.S., M. MacDonald, and A. Eden. 1988. An Overview of 3-D Graphical Analysis Using DOE-2 Hourly Simulation Data, *ASHRAE Transactions* 94(1), 212-227.

Haberl, J.S., and P.S. Komor. 1989. *Investigating an Analytical Basis for Improving Commercial Energy Audits: Early Results from a New Jersey Mall, Thermal Performance of the Exterior Envelopes of Buildings IV*, American Society of Heating, Refrigerating and Air Conditioning Engineers (ASHRAE), Atlanta, GA.

Haberl, J.S. 1993. *Economic Calculations for ASHRAE Handbook*. Energy Systems Laboratory Report EST-TR-93/04-07, College Station, TX: Texas A&M University.

Haberl, J.S., and T.E. Bou-Saada. 1998. Procedure for Calibrating Hourly Simulation Models to Measured Building Energy and Environmental Data. *ASME Journal of Solar Energy Engineering* 120(August):193-213.

Haberl, J., T. Bou-Saada, V. Soebarto, and A. Reddy. 1998. Use of Calibrated Simulation for the Evaluation of Residential Energy Conservation Options of Two Habitat for Humanity Houses in Houston, Texas. *The Eleventh Symposium on Improving Building Systems in Hot and Humid Climates Proceedings,* 359-369, June 1-2, 1998. Radisson Plaza Hotel, Forth Worth, TX.

Harbi, Y.A., Eugenio N. N., Zahrani S. Al. 1998. Photovoltaic-Thermal Solar Energy Experiment in Saudi Arabia, *Renewable Energy* 15, 483-486.

Hendrie S. D. 1979. Combined Photovoltaic/Thermal Collector Performance, *Proceedings of International Solar Energy Society Conference (ISES)*, Atlanta, GA.

Hinchey, S.B. 1991. *Influence of Thermal Zone Assumptions on DOE-2 Energy Use Estimations of a Commercial Building*, Master's thesis, Texas A&M University, College Station, TX.

Hsieh, E.S. 1988. *Calibrated Computer Models of Commercial Buildings and Their Role in Building Design and Operation*, Master's thesis, Princeton University, Princeton, NJ.

Hsieh, E.S., L.K. Norford, R.H. Socolow, and G.V. Spadaro. 1989, *Calibrated Computer Models to Track Building Energy Use: The Role of Tenant and Operator Decisions* (Private Collection, T.Bou-Saada), Energy Systems Laboratory, Texas A&M University, College Station, TX.

Huang, B. J., Lin T. H., Hung W. C., and Sun F. S. 2001. Performance Evaluation of Solar Photovoltaic/Thermal Systems, *Solar Energy* 70(5), 443-448.

Huang & Associates. 2000. *DrawBDL User's Guide*, El Cerrito, CA.

Humanist Co.,Ltd. 2000. Energy Saving House, *The Energy Efficiency Journal* 48, 27-29.

Imre, L., Böhönyey, F., Hecker, G., and Pálfy, M. 1993. PV-Thermal Combined Building Elements, *Proceedings of International Solar Energy Society Conference (ISES),* Budapest, Hungary.

International Electrotechnical Commission (IEC). 1998. *International Standard IEC 61724: Photovoltaic System Performance Monitoring Guidelines for Measurement*, Data Exchange and Analysis, Geneva, Switzerland.

Jitkhajornwanich, K. 1998. Thermal Comfort in Transitional Spaces in the Cool Season of Bangkok. *ASHRAE Technical Data Bulletin* 14(1), 112-124.

Kalogirou, S.A. 2001. Use of TRNSYS for Modeling and Simulation of a Hybrid PV-Thermal System for Cyprus. *Renewable Energy* 23, 247-260.

Kaplan, M.B., B. Jones, and J. Jansen. 1990a. DOE-2.1C Model Calibration with Monitored End-Use Data, *Proceedings from the ACEEE 1990 Summer Study on Energy Efficiency in Buildings*, Vol. 10, 10.115-10.125, American Council for an Energy Efficiency Economy, Washington, DC.

Kaplan, M.B., J. McFerran, J. Jansen, and R. Pratt. 1990b. Reconciliation of a DOE-2.1C Model with Monitored End-use Data for a Small Office Building, *ASHRAE Transactions*. 96(1): 981-993.

Kaplan, M.B., P. Caner, and G.W. Vincent. 1992. Guidelines for Energy Simulation of Commercial Buildings, *Proceedings from the ACEEE 1992 Summer Study on Energy Efficiency in Buildings 1*, 1.137-1.147., American Council for an Energy Efficient Economy, Washington, DC.

Khedari, J., Waewsak, J., Thepa, S., and Hirunlabh, J. 2000. Field Investigation of Night Radiation Cooling under Tropical Climate, *Renewable Energy* 20, 183-193.

Klein, S.A. and Beckman W.A. 1985. *F-Chart User's Manual Microcomputer Version*, Solar Energy Laboratory, University of Wisconsin, Madison, WI.

Klein, S.A. and Beckman W.A. 2001. *PV F-Chart User's Manual Windows Version*, Solar Energy Laboratory, University of Wisconsin, Madison, WI.

Klima, P. M. 2000. *Improving the Reliability and Accuracy of a Multipyranometer Array Measuring Solar Radiation.* Master's thesis, Texas A&M University, College Station, TX.

Kreider, J., and J. Haberl. 1994. Predicting hourly building energy usage: The great energy predictor shootout: Overview and discussion of results. *ASHRAE Transactions Technical Paper* 100(2): 56-70.

Kreider, J. and Rabl, A. 1994. *Heating and Cooling of Buildings: Design for Efficiency*. McGraw-Hill, Inc., New York.

Krissanapong, K. 1997. Photovoltaic Application in Thailand: Twenty Years of Planning and Experience, *Solar Energy Material and Solar Cells* 47**,** 55-62.

Kusuda, T. 1965. Earth Temperature and Thermal Diffusivity at Selected Stations in the United States. *ASHRAE Semiannual Meeting Proceedings (article no. 1914).* Jan. 25-28, 1965. Chicago, Illinois.

Lawrence Berkeley National Laboratory (LBNL) 1982. *The DOE-2 Reference Manual Version 2.1A*, Lawrence Berkeley National Laboratory, Berkeley, CA.

Lawrence Berkeley National Laboratory (LBNL) 1993. *The DOE-2 Supplement Version 2.1E*, Lawrence Berkeley National Laboratory, Berkeley, CA.

Lawrence Berkeley National Laboratory (LBNL) 1999. *The DOE-2.1E Corrections and Bug Fixes*, Lawrence Berkeley National Laboratory, Berkeley, CA.

Lawrence Berkeley National Laboratory (LBNL) 2001. *The DOE-2.1E Documentation Update Package #4*, Lawrence Berkeley National Laboratory, Berkeley, CA.

Leenders, F., and Sørensen, H. 2000. *Draft 'Road Map'on PV/T Systems, ECOFYS*, Ulrecht, The Netherlands.

LI-COR, Inc. 1991. *The Terrestrial Radiation Sensors, Type SA Instruction Manual*, Li-Cor Inc., Lincoln, Nebraska.

Manke, J.M., D.C. Hittle, and C.E. Hancock. 1996. Calibrating building energy analysis models using short term test data. *Proceedings of the 1996 International ASME Solar Energy Conference* (p.369-378). San Antonio, TX.

Martin, M. 1989. Radiative Cooling. In *Passive Cooling*, Bankston C. A. (Series Ed.) and Cook J. (Vol. Ed.), pp.139-196, The MIT Press, Cambridge, MA.

Maycock, P. 2004. The State of the PV Market. *Solar Today*, (18)1, 32-35.

Metropolitan Electricity Authority of Thailand (MEA) 2000. *Energy Consumption 2000 Report,* Bangkok, Thailand.

Ministry of Science and Technology (MOST) 1998. *Refrigerator*, C&S Printing Co., Ltd., Bangkok, Thailand.

Muntasser, M. A., Bara, M.F., Quadri, H.A., EL-Tarabelsi, R., La-azebi, I.F. 2000. Photovoltaic Marketing in Developing Countries. *Applied Energy* 65, 67-72.

National Statistical Office (NSO). 1996 *Report on Housing Survey 1996*, Bangkok, Thailand.

National Statistical Office (NSO). 2000a. *Report of the Household Energy Consumption Survey 2000*, Bangkok, Thailand.

National Statistical Office (NSO) 2000b. *The 2000 Population and Housing Census and Preliminary Report*, Bangkok, Thailand.

Newton A. B. and Gilman S. F. 1981. *Solar Collector Performance Manual,* ASHRAE Inc., Atlanta, GA.

Oh, K.W. 2000. *Development and Validation of a Computer Model for Energy-efficient Shaded Fenestration Design.* Ph.D. dissertation, Texas A&M University, College Station, TX.

Onset Computer Corporation. 2000. *HOBO H8 Family User's Manual*, Onset Computer Corporation, Bourne, MA.

Parker D. S. 1991. Residential Demand Site Management for Thailand, prepared for the International Institute for Energy Conservation, FSEC-CR-423-91, Florida Solar Energy Center, Cape Canaveral, FL, June 1991.

Parker D. S. 1995. Measured Air Conditioning and Thermal Performance of a Thai Residential Building. *Energy* 20, 907-914.

Rockendorf G., Silimann R., Podlowski L., and Litzenburger B. 1999. PV-Hybrid and Thermoelectric Collectors, *Solar Energy* 67(4-6), 227-237.

Saitho T. S. and Fujino T. 2001. Advanced Energy-Efficient House (Harbeman House) with Solar Thermal, Photovoltaic, and Sky Radiation Energies (Experimental Results). *Solar Energy* 70(1), 63-77.

Sandnes, B. and Rekstad, J. 2002. A Photovoltaic/Thermal (PV/T) Collector with a Polymer Absorber Plate: Experimental Study and Analytical Model, *Solar Energy* 72(1), 63-73.

Sørensen H., and Munro D. 2000. Hybrid PV/Thermal Collectors, *The 2nd World Solar Electric Building Conference*, Sydney, March 2000, pp. 1-7.

Sopian K., Yigit K. S., Liu H. T., Kakac S., and Veziroglu T. N. 1995. Performance Analysis of Photovoltaic Thermal Air Heaters, *Energy Conversion and Management* 37, 1657-1670.

Sreshthaputra, A. 2003. *Building Design and Operation for Improving Thermal Comfort in Naturally Ventilated Building in a Hot-humid Climate.* Doctoral dissertation, Texas A&M University, College Station, TX.

Stein, B. and Reynolds, J.S. 1992. *Mechanical and Electrical Equipment for Buildings (8th et).* New York, NY: John Wiley & Sons, Inc.

Swiss Federal Office of Energy (SFOE) 2000. *New Generation of Hybrid Solar PV/T Collectors*, Final Report DIS 56360/16868.

Thai Gypsum Products Public Company Limited (TGPPC). 1996. *Energy Efficient Design of Buildings in Thailand*, Bangkok, Thailand.

Thongpiyapoom, A. 1996. *Heat avoidance and passive cooling strategies for typical houses in Bangkok, Thailand*. Master's thesis, Texas A&M University, College Station.

Tripanagnostopoulos, Y., Yianoulis, P., and Patrikios, D. 1996. *Hybrid PV-TC Solar Systems*, WREC, Denver, CO.

Tripanagnostopoulos, Y., Nousia, T., Souliotis, M., and Yianoulis, P. 2002. Hybrid Photovoltaic/Thermal Solar Systems, *Solar Energy* 72(3), 217-234.

Watson, D. (Eds.) 1993. *The Energy Design Handbook.* Washington, DC: The American Institute of Architects Press.

Wise, J.A. and R.J. Soulen, Jr. 1986. *Thermometer Calibration: A Model for State Calibration Laboratories*. Washington, DC: U.S. Government Printing Office.

Zondag, H.A., de Vreis, D.W., van Helden, G.J. van Zolingen, R.J.C. and van Steenhoven, A.A. 2002. Thermal and Eletrical Yield of a PV-Thermal Collector, *Solar Energy* 72(2), 113-128.

APPENDIX A

MEASURED DATA FROM THE CASE-STUDY HOUSE

Measured temperatures and humidities in the case-study house are presented in Section A.1 and A.2, respectively. Calibrations of the portable data loggers used for measuring and recoding temperature and humidity in the case-study house are presented in Appendix C.

A.1 Measured Temperatures in the Case-Study House

Measured temperatures in four spaces of the case-study house compared with outdoor temperatures are presented in time series plots in Figure A.1 to A.4. The measured data were obtained by on-site measurements of indoor conditions of the case-study house from four measurement devices (portable data loggers), including: one in an air-conditioned space, two in unconditioned spaces (1st floor and 2nd floor spaces), and one in the attic space. Figure A.1 shows measured temperatures of living-dining room, which was an unconditioned space on the ground floor, compared with the outdoor temperatures. Figure A.2 shows measured temperatures of bedroom-3, which was an unconditioned space on the second floor, compared with the outdoor temperatures. Figure A.3 shows measured temperatures of master bedroom, which was a conditioned space on the second floor, compared with the outdoor temperatures. Figure A.4 shows measured attic temperatures compared with the outdoor temperatures. The outdoor temperatures plotted in Figure A.1 to A.4 were Bangkok weather data 2000 that was directly obtained from the Thai Meteorological Department.

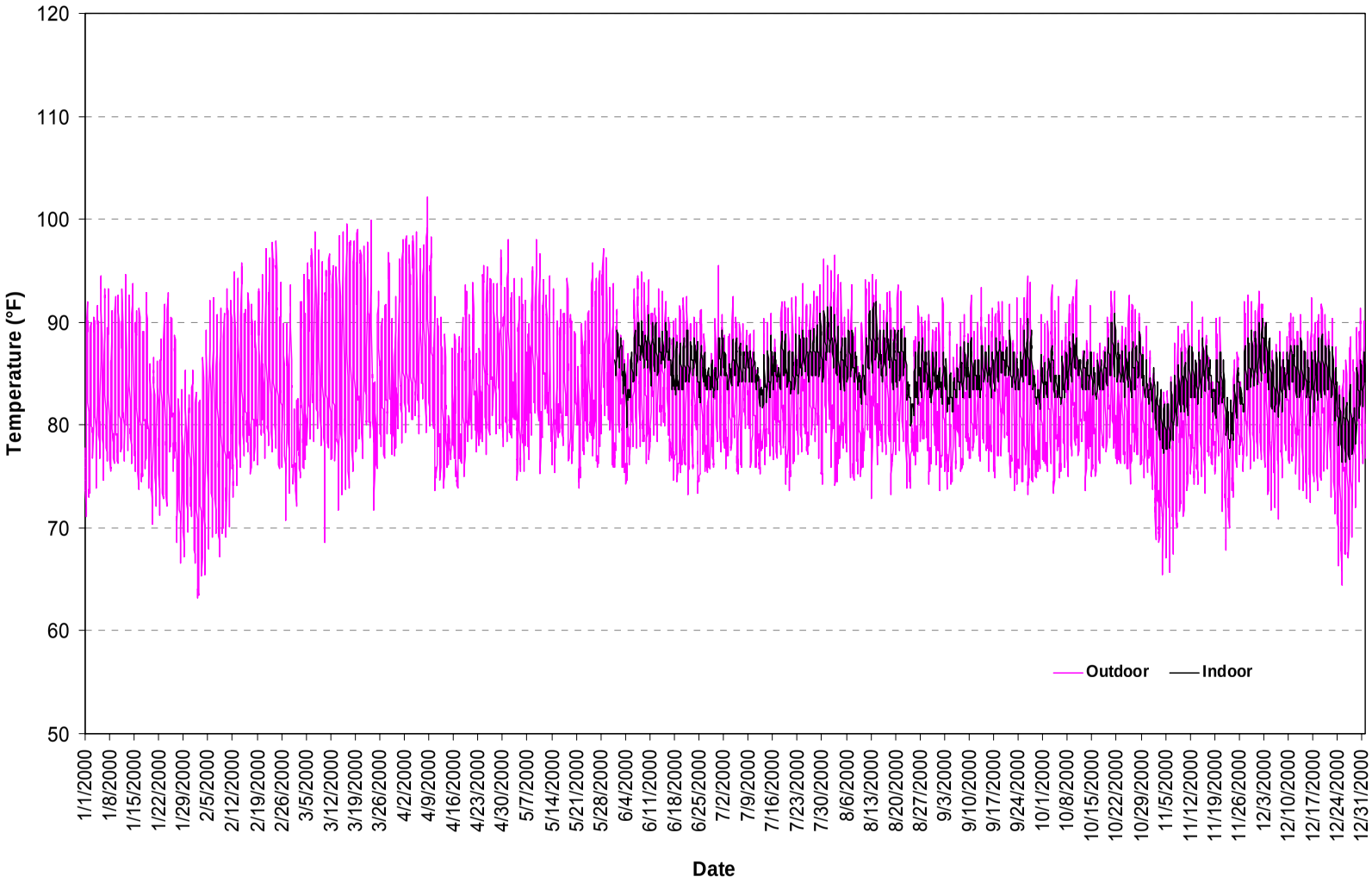


Figure A.1 *Measured Living-dining Room Temperatures Compared with the Corresponding Outdoor Temperatures*

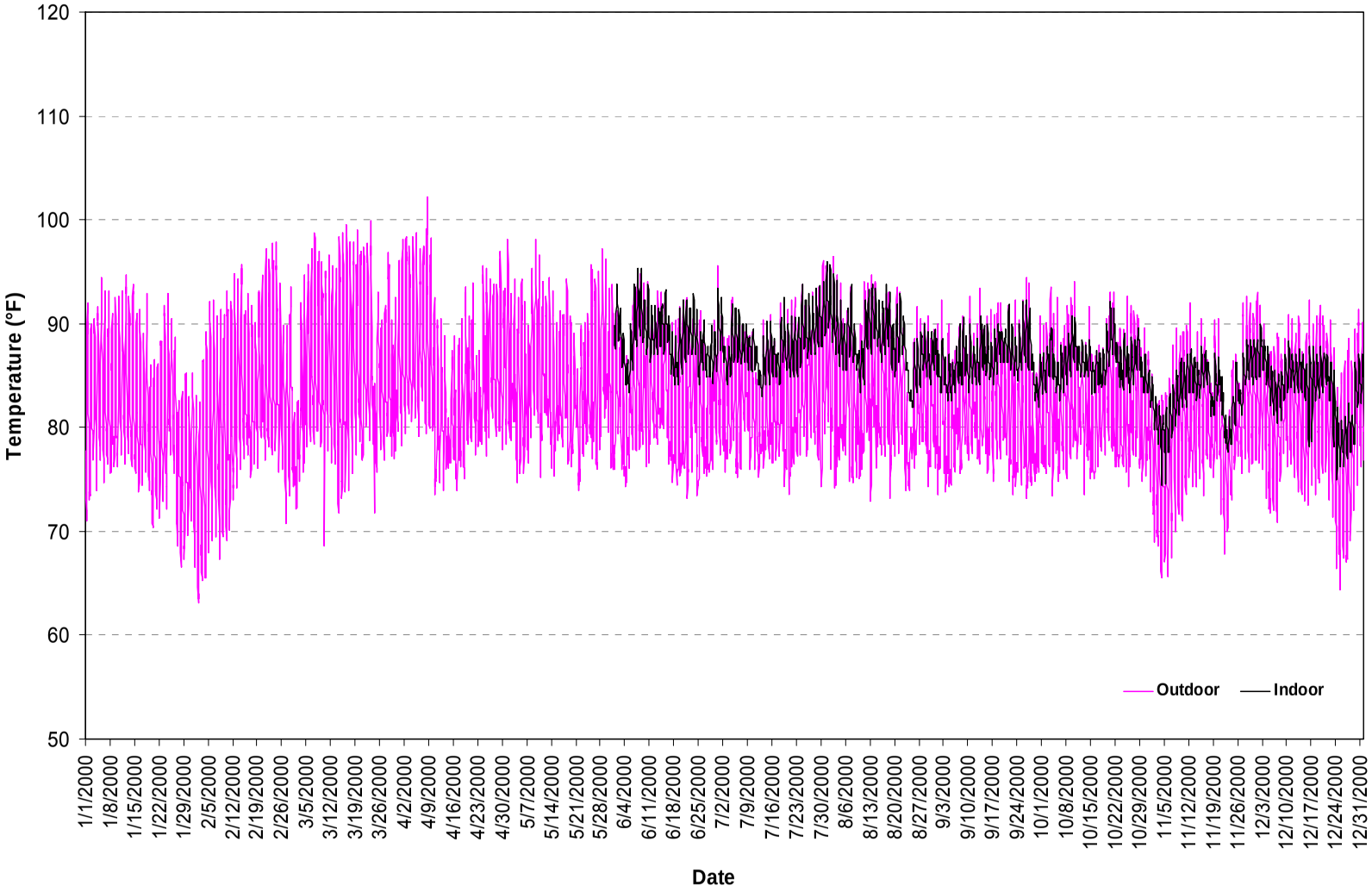


Figure A.2 *Measured Bedroom-3 Temperatures Compared with the Corresponding Outdoor Temperatures*

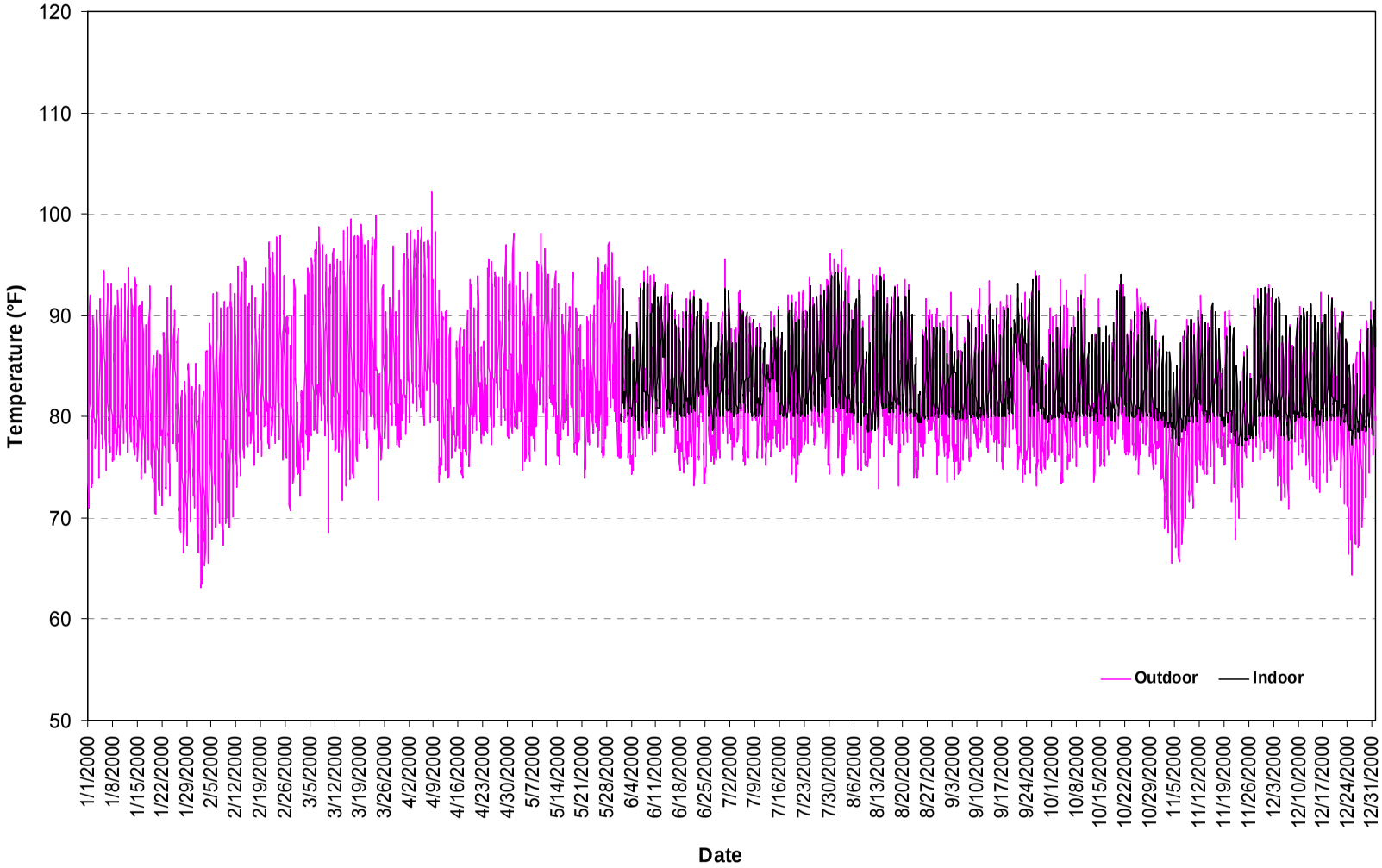


Figure A.3 *Measured Master Bedroom Temperatures Compared with the Corresponding Outdoor Temperatures*

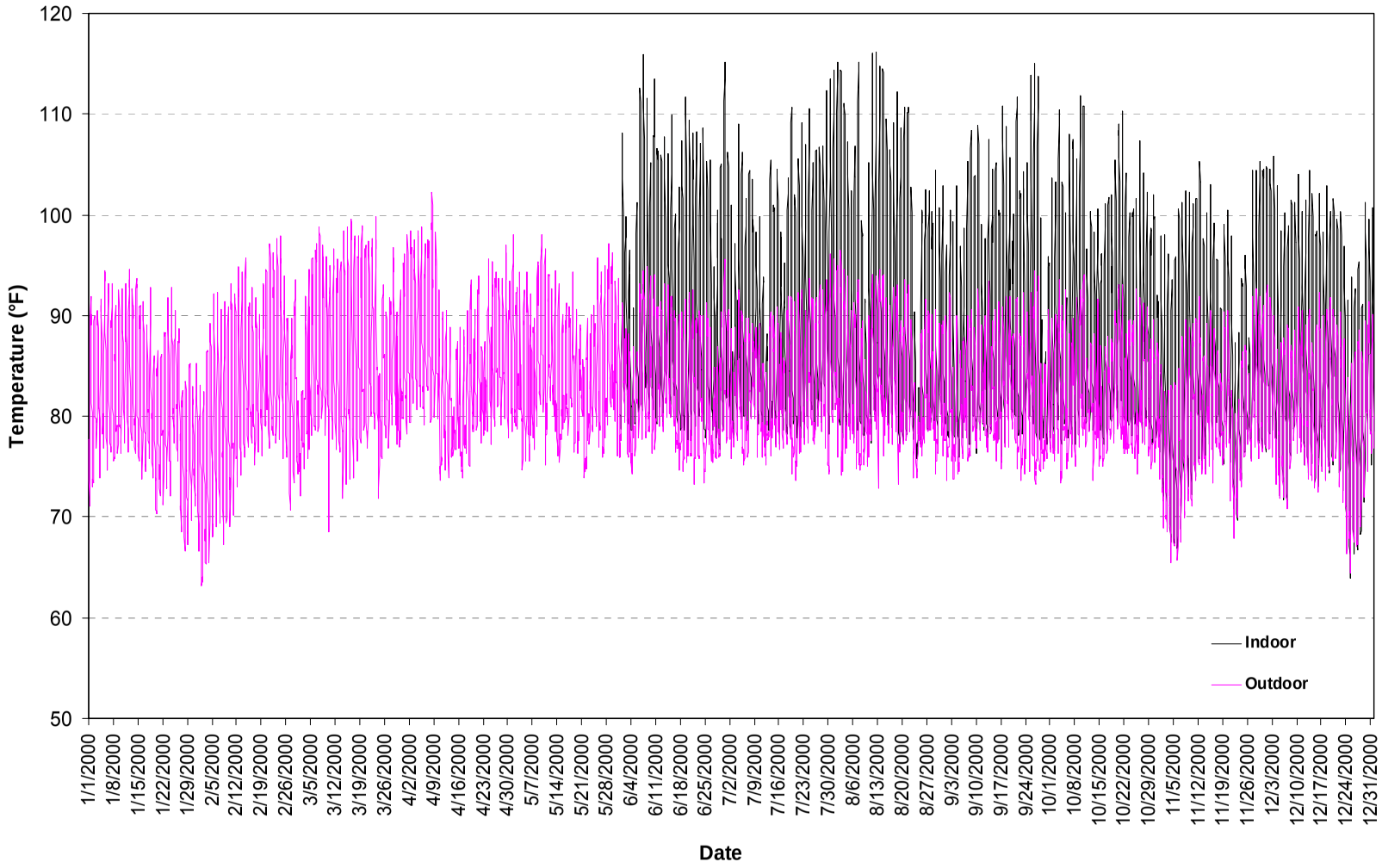


Figure A.4 *Measured Attic Temperatures Compared with the Corresponding Outdoor Temperatures*

A.2 Measured Relative Humidities in the Case-Study House

Measured relative humidities in three living spaces of the case-study house compared with outdoor humidity are presented in time series plots in Figure A.5 to A.7. The measured data were obtained by on-site measurements of indoor humidities of the case-study house from three measurement devices (portable data loggers), including: one in an air-conditioned space, and two in unconditioned spaces (1st floor and 2nd floor spaces). Figure A.5 shows measured relative humidities of living-dining room, which was an unconditioned space on the ground floor, compared with the outdoor relative humidities. Figure A.6 shows measured relative humidities of bedroom-3, which was an unconditioned space on the second floor, compared with the outdoor relative humidities. Figure A.7 shows the measured relative humidities of the master bedroom, which was a conditioned space on the second floor, compared with the outdoor relative humidities. The outdoor relative humidities plotted in Figure A.5 to A.7 were Bangkok weather data 2000 that was directly obtained from the Thai Meteorological Department.

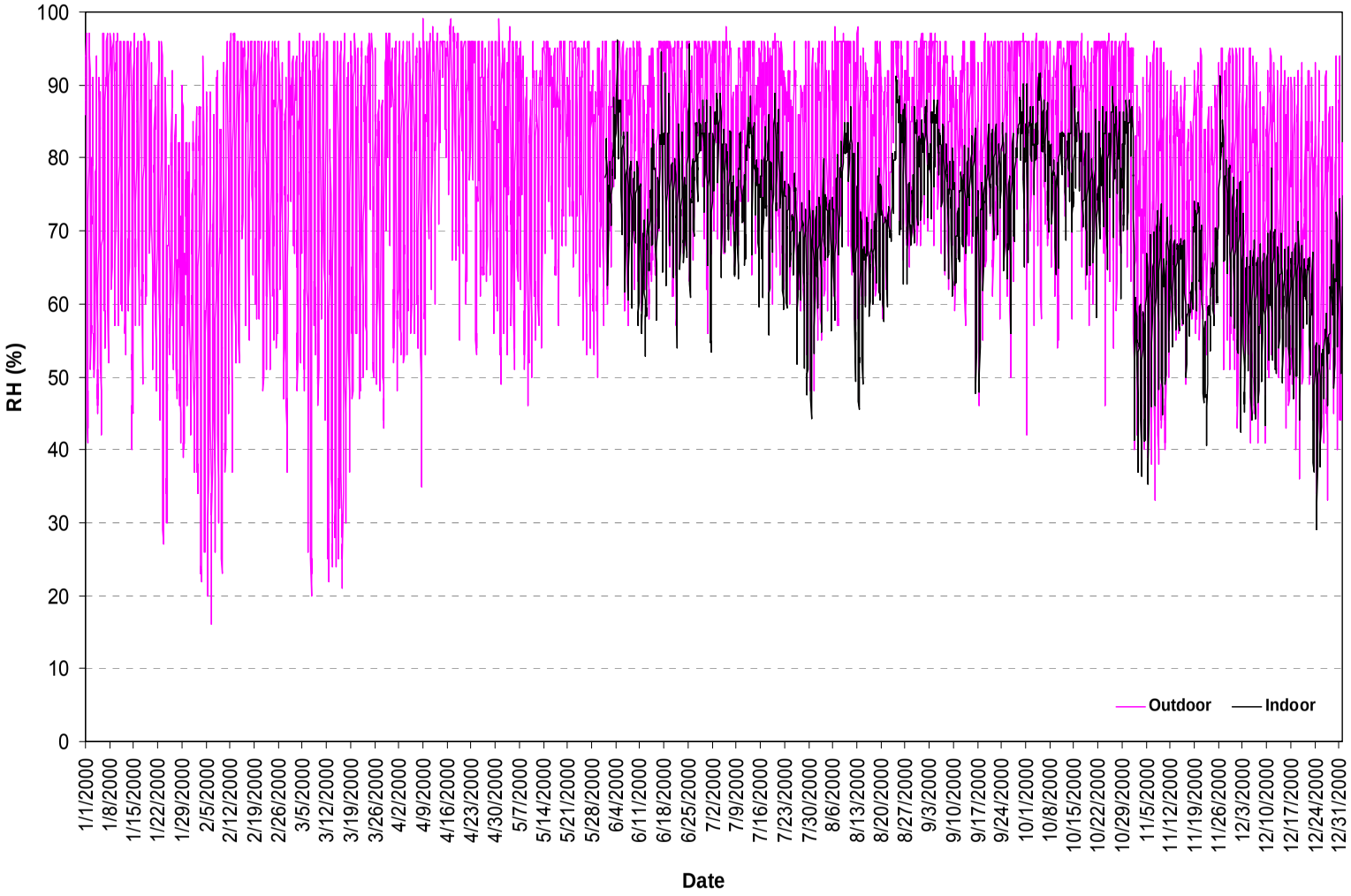


Figure A.5 *Measured Living Room Relative Humidities Compared with the Corresponding Outdoor Humidities*

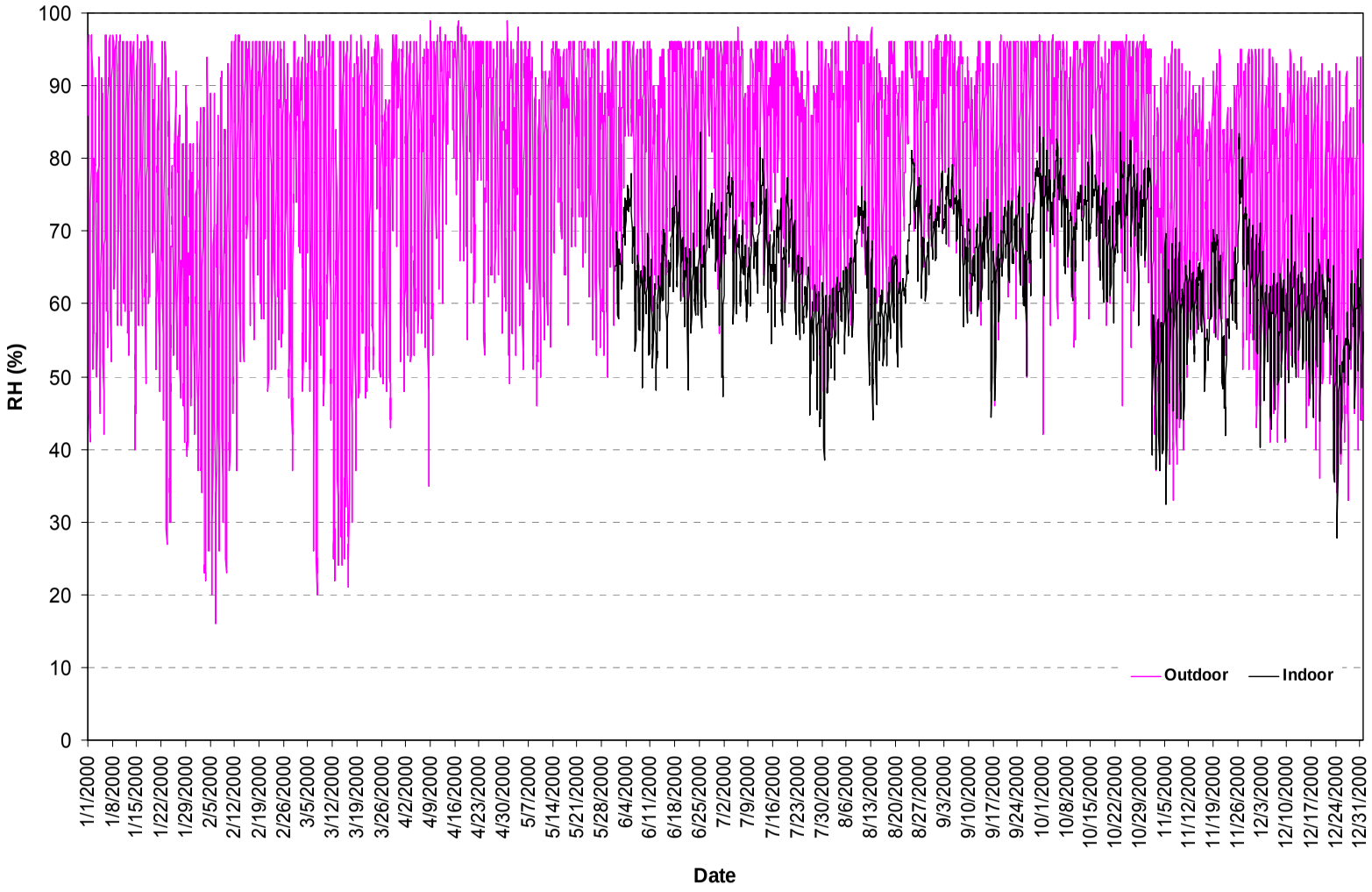


Figure A.6 *Measured Bedroom-3 Relative Humidities Compared with the Corresponding Outdoor Humidities*

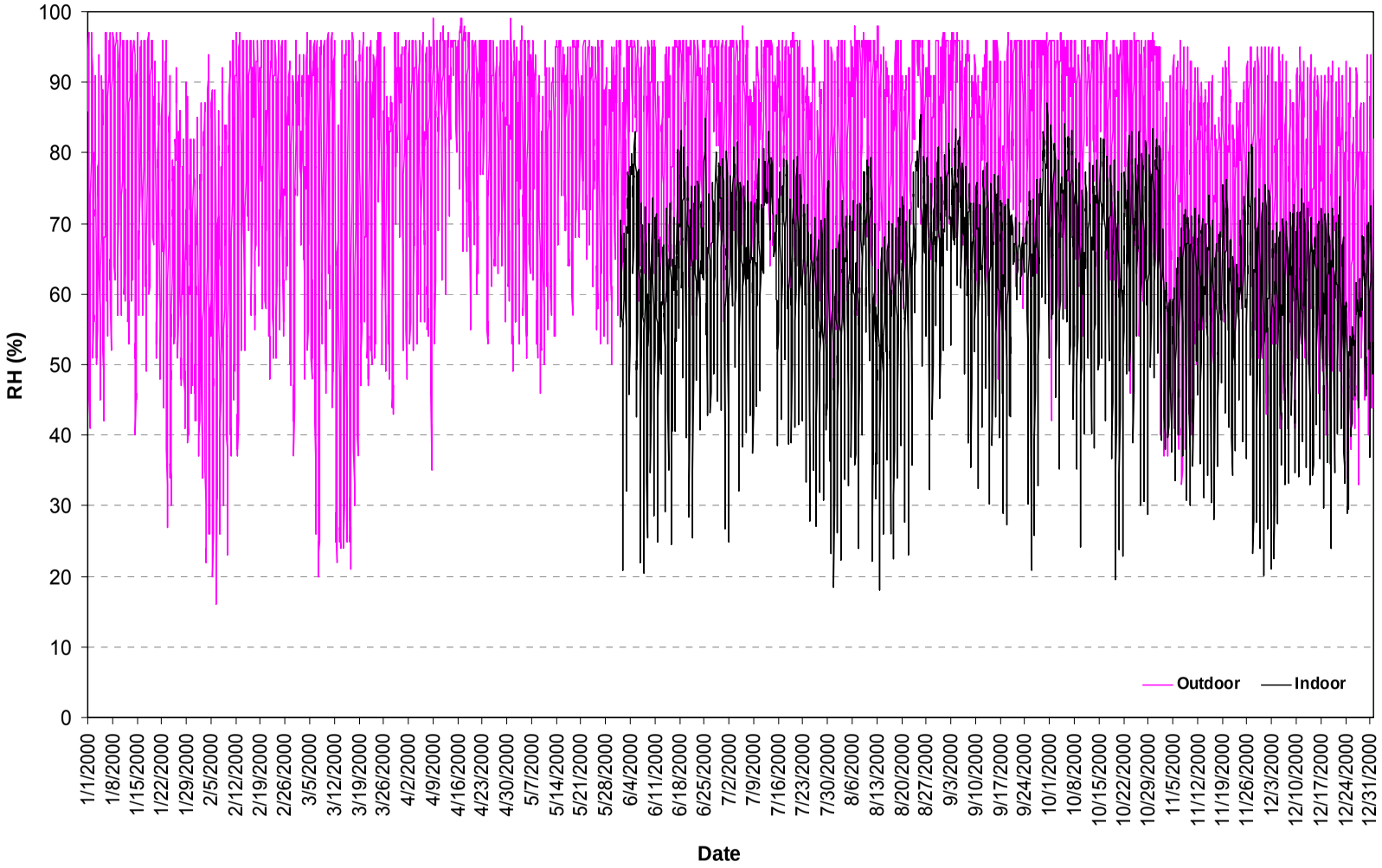


Figure A.7 *Measured Master Bedroom Relative Humidities Compared with the Corresponding Outdoor Humidities*

APPENDIX B

THE EXPERIMENTAL BOX

B.1 Construction of Experiment Box and Measurement Devices

Figure B.1 *Construction of the Experiment Box: (a) the insulated base, (b) walls were built in modules, (c) the beam over the doors was installed, (d) a close-up of joint of the beam, (e) the inside of the roof-insulated with fiberglass, and (f) the roof after cover with the roofing material.*

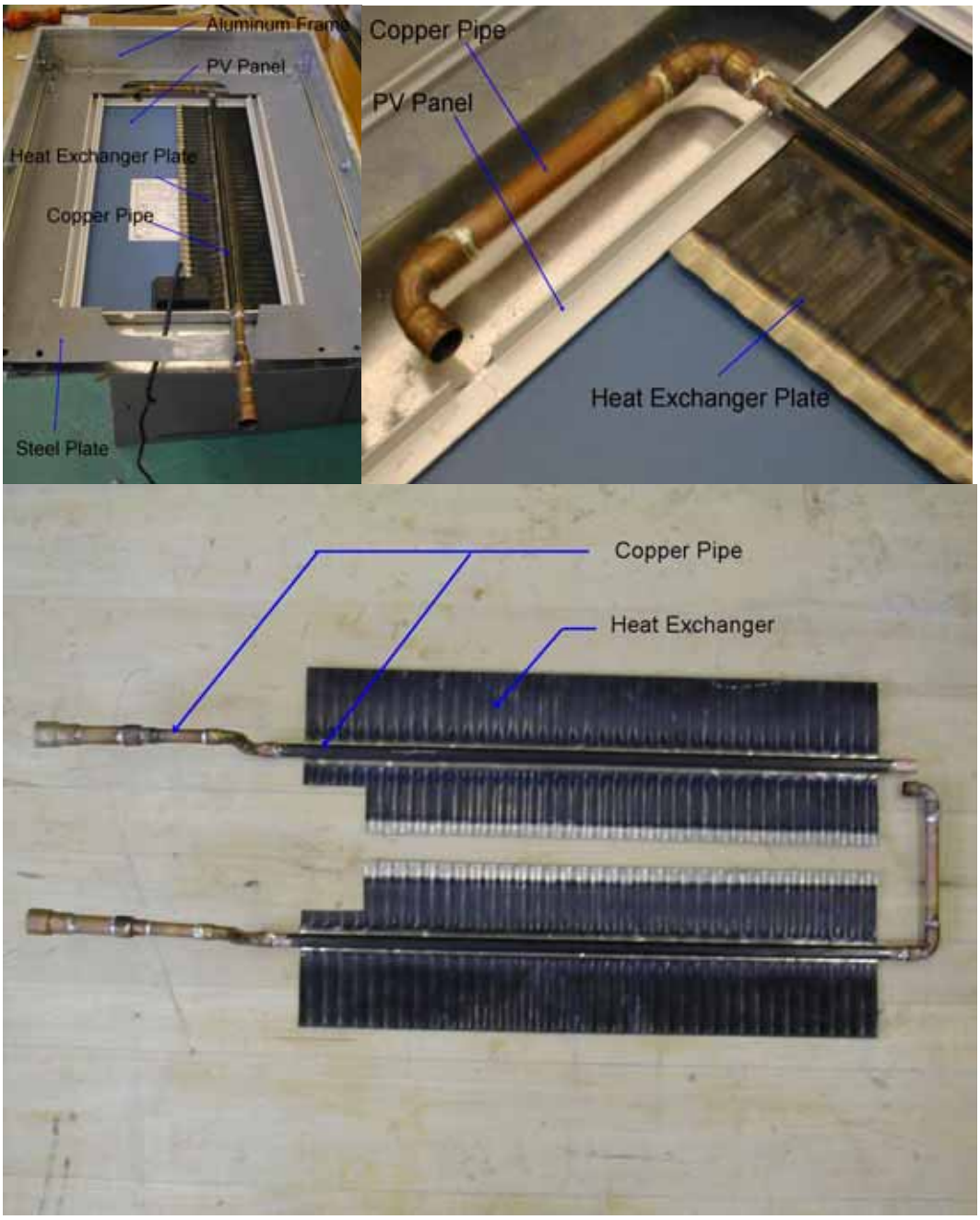


Figure B.2 *Construction of the Energy Collector/Rejecter Unit. The bottom part of the picture is the heat exchanger that was modified from a solar collector absorber plate. The upper left part of the picture is the heat exchanger placed on the back of the PV panel. The upper right part of the picture shows a close-up of heat exchanger and the PV panel. As it can be seen, the PV's aluminum frame needed to be lathed to accommodate the pipe.*

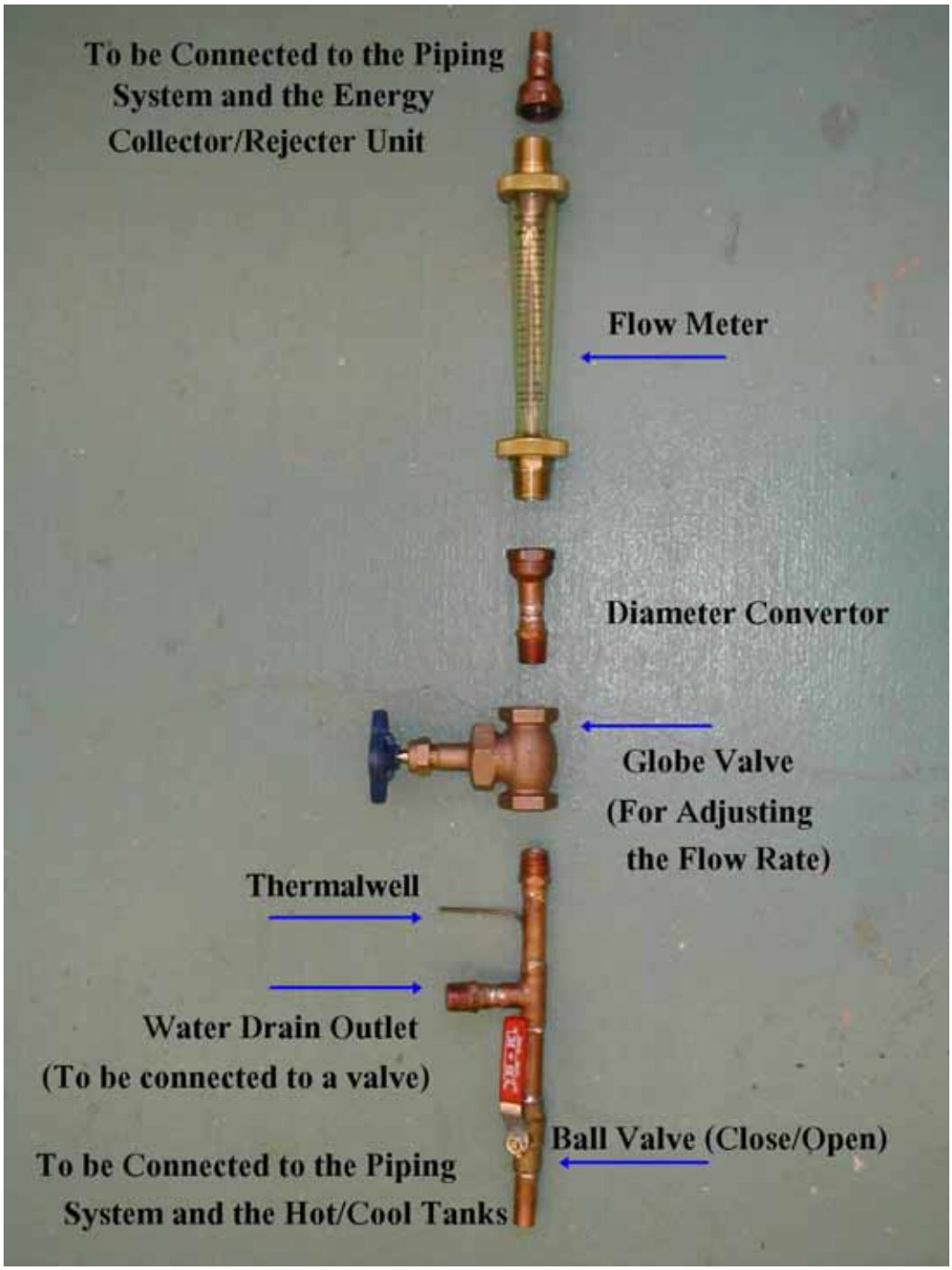


Figure B.3 *Water Flow Rate Controlling System. The above picture shows part of the piping system before assembling which includes thermalwell, globe valve, and flow meter. Thermalwell is a small pipe that was extended into the pipe. A thermocouple was inserted into the thermalwell to measure the temperature of water in the pipe.*

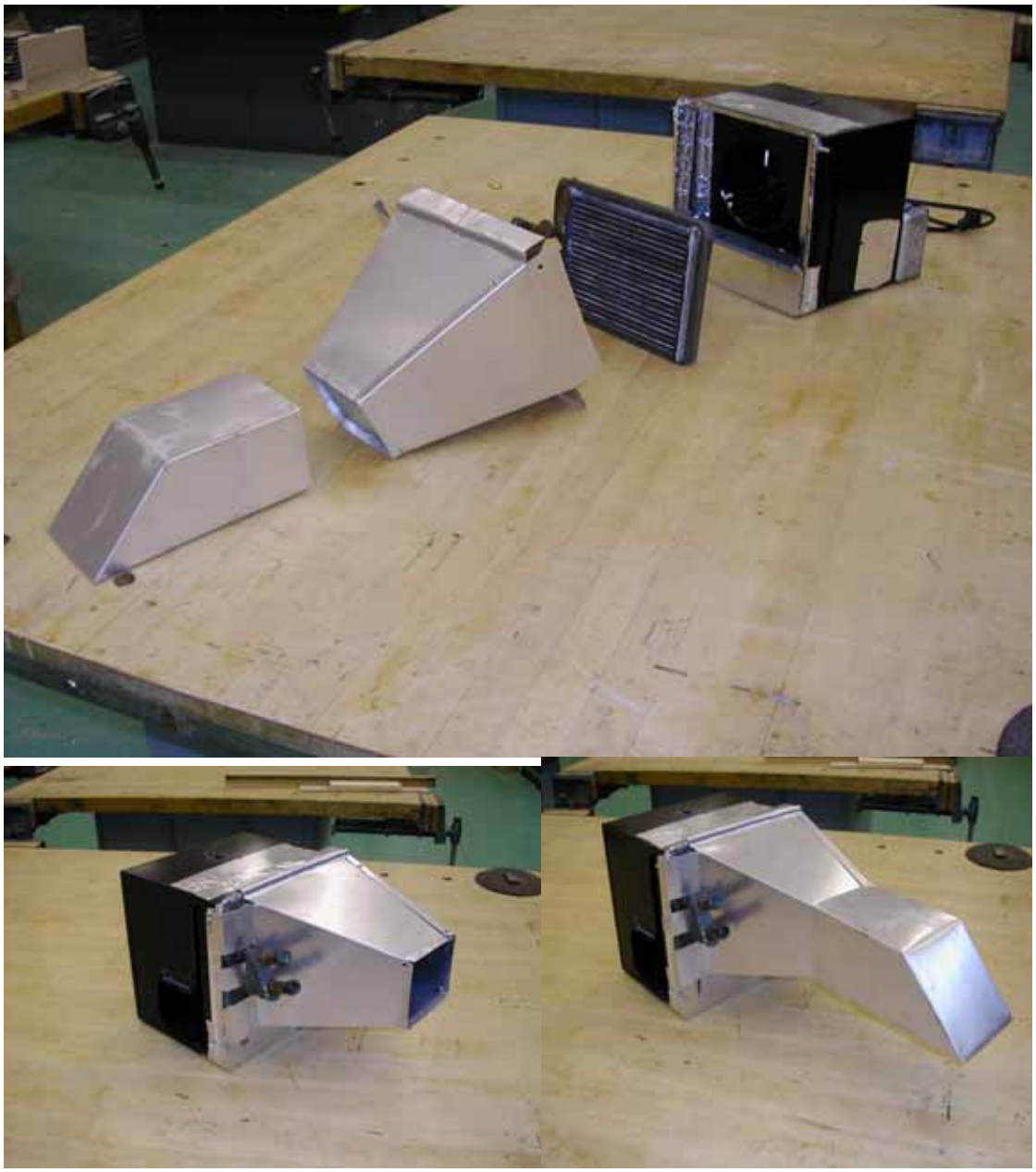


Figure B.4 *Construction of the Heat Rejecter. The heat rejection box was custom made from an automobile radiator (as seen in the top picture), a blower, and aluminum plates. The heat rejection box is part of the Water Temperature Regulating Systems that was explained in Section 4.2.2.2.*

B.2 Input Program for the Campbell 21X Data Logger

The following is the description of an input file created by SCWIN to program the Campbell 21X data logger. SCWIN, which is a subprogram in PC200W, is used to create input file for the logger (Campbell Scientific, Inc., 2001). The logger can also be programmed directly (without PC200W) using the keyboard on the logger's panel (Campbell Scientific, Inc., 1989).

```
7/18/2002
15:35:14
Created by SCWIN (Version 1.1)
SCWIN Program:  Li-Temp.DEF
-Wiring for 21X-

 LI200S Pyranometer
   1H:   Red
   1L:   Black
   GROUND:   Clear

 Type T (copper-constantan) Thermocouple (1)
   2H:   Blue
   2L:   Red

 Type T (copper-constantan) Thermocouple (2)
   3H:   Blue
   3L:   Red
 Type T (copper-constantan) Thermocouple (3)
   4H:   Blue
   4L:   Red

 Type T (copper-constantan) Thermocouple (4)
   5H:   Blue
   5L:   Red

 Type T (copper-constantan) Thermocouple (5)
   6H:   Blue
   6L:   Red

 Differential Voltage
   GROUND:   Shield
   7H:   High
   7L:   Low

 4-20 mA Input
   GROUND:   Jumper to 4-20 mA Low
   8H:   High
   8L:   Low
```

B.3 Results from the Day Mode Experiment

This section presents the measured data and results of the day mode experiment. The results of eight days of the day mode experiments are shown in Figure B.5 to B. 16. The results of thermal and electrical experiment of the hybrid PV-T^2 collector system are shown in those figures except the results from the experiments on November 6 and 7, 2002 that there are only the results of thermal energy. As it was explained in Chapter VI, Section 6.2, there was a problem with the resistor circuit board, so electricity output from the PV could not be measured on both days.

B.4 Results from the Night Mode Experiment

This section presents the measured data and results of the night mode experiment. The results of twelve nights of the night mode experiment are shown in Figures B. 17 to 27.

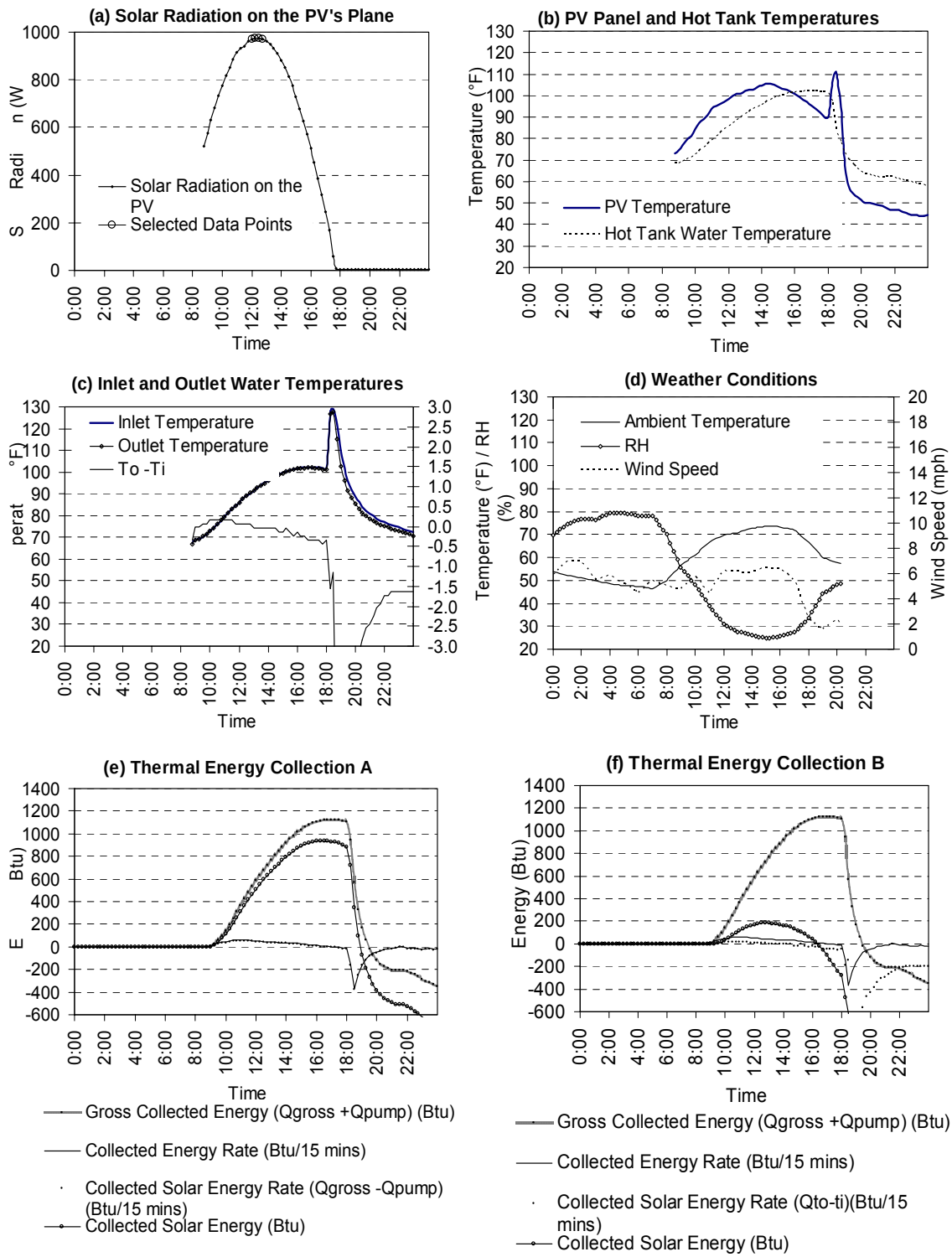


Figure B.5 *Results from Day Mode Experiment on November 6, 2002.*

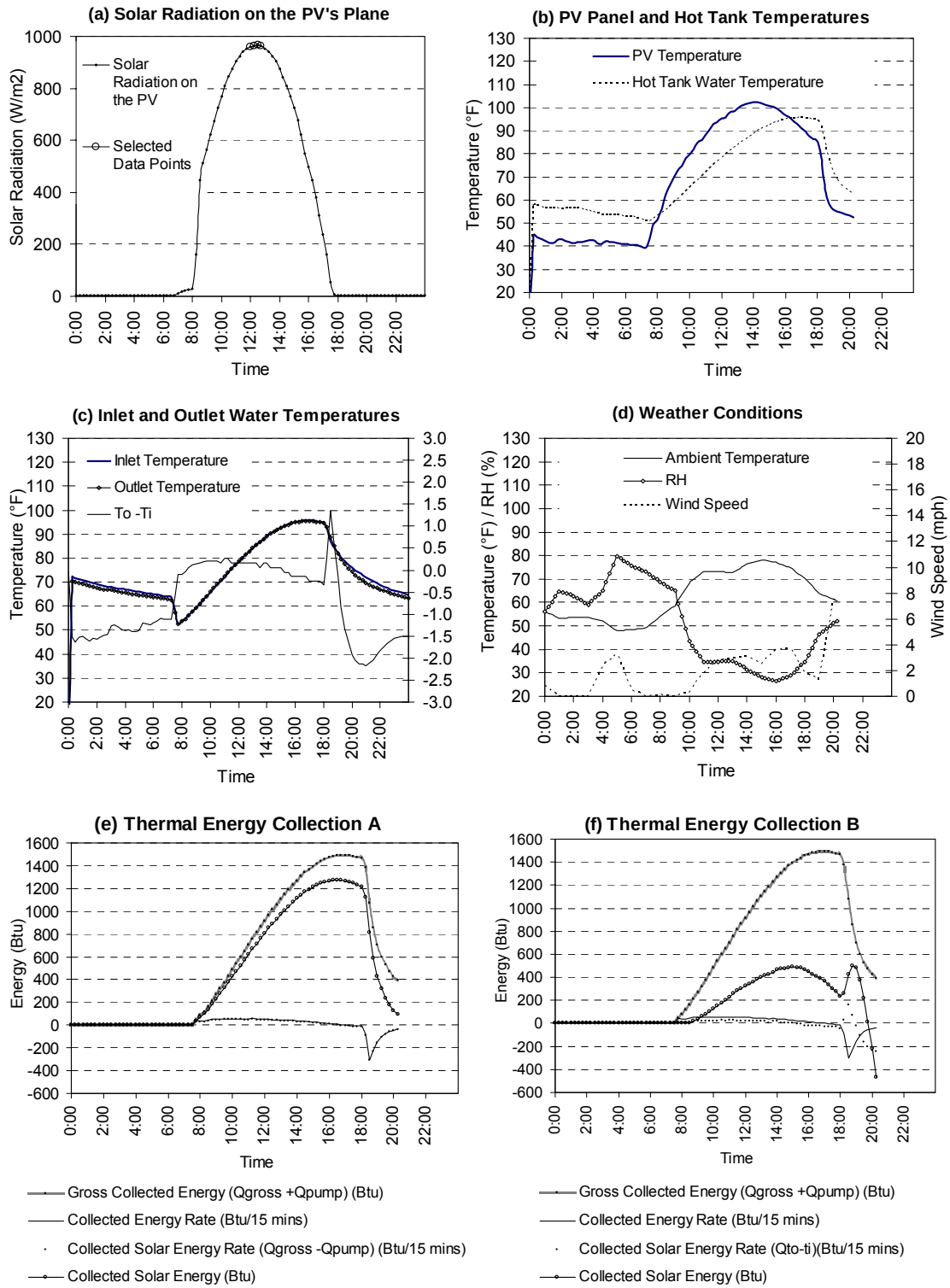


Figure B.6 *Results from Day Mode Experiment on November 7, 2002.*

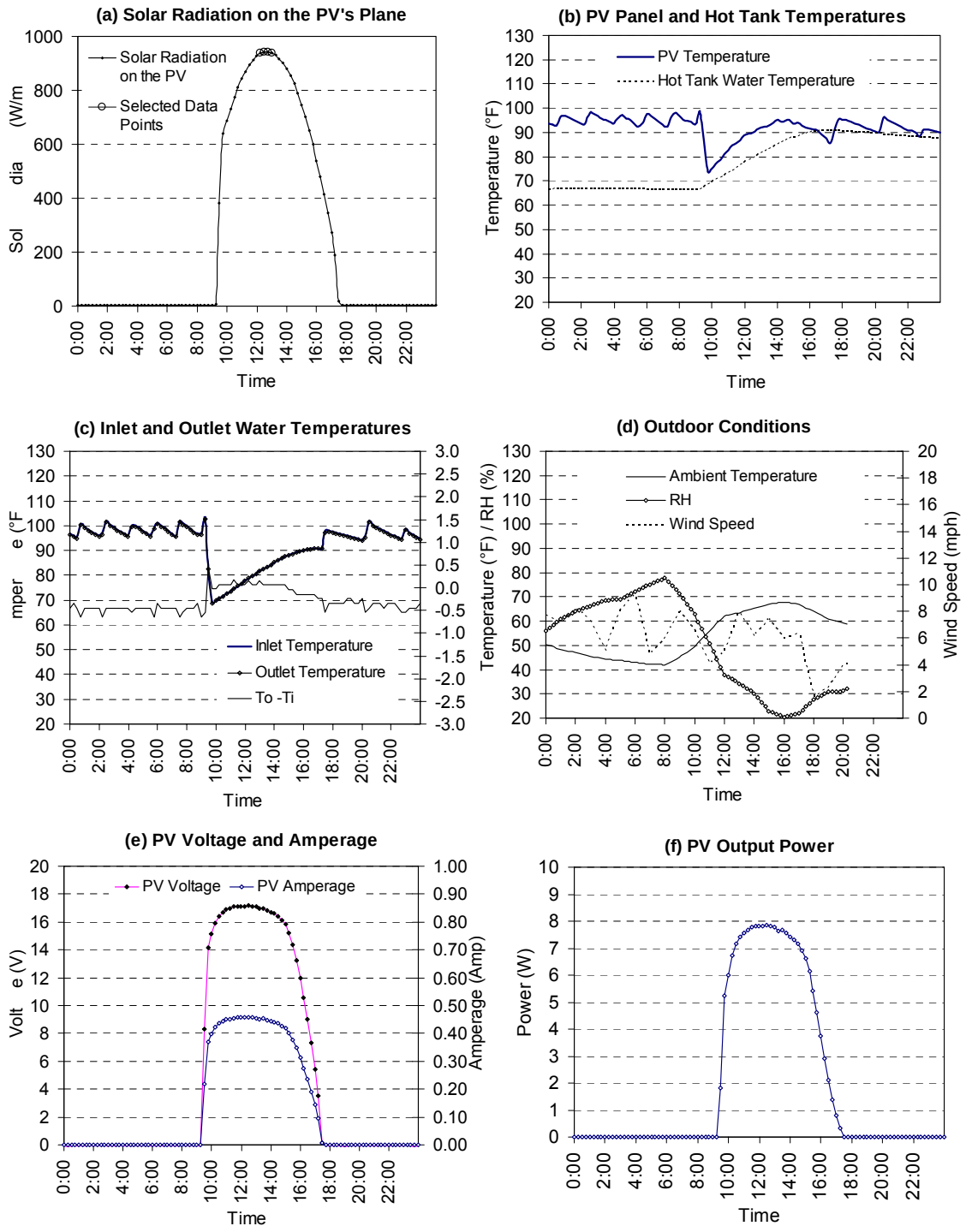


Figure B.7 *Results from Day Mode Experiment on December 20, 2002.*

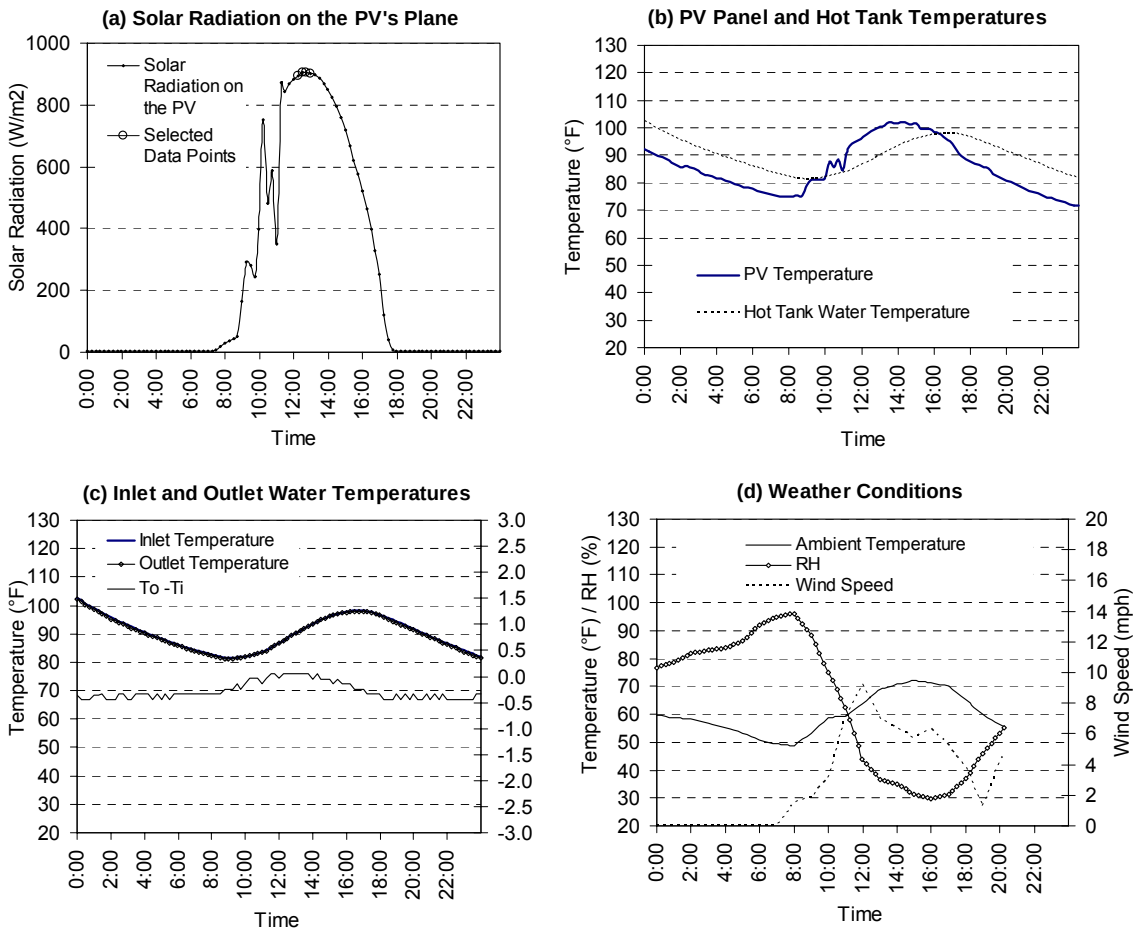


Figure B.8 *Results (a-d) from Day Mode Experiment on January 6, 2003.*

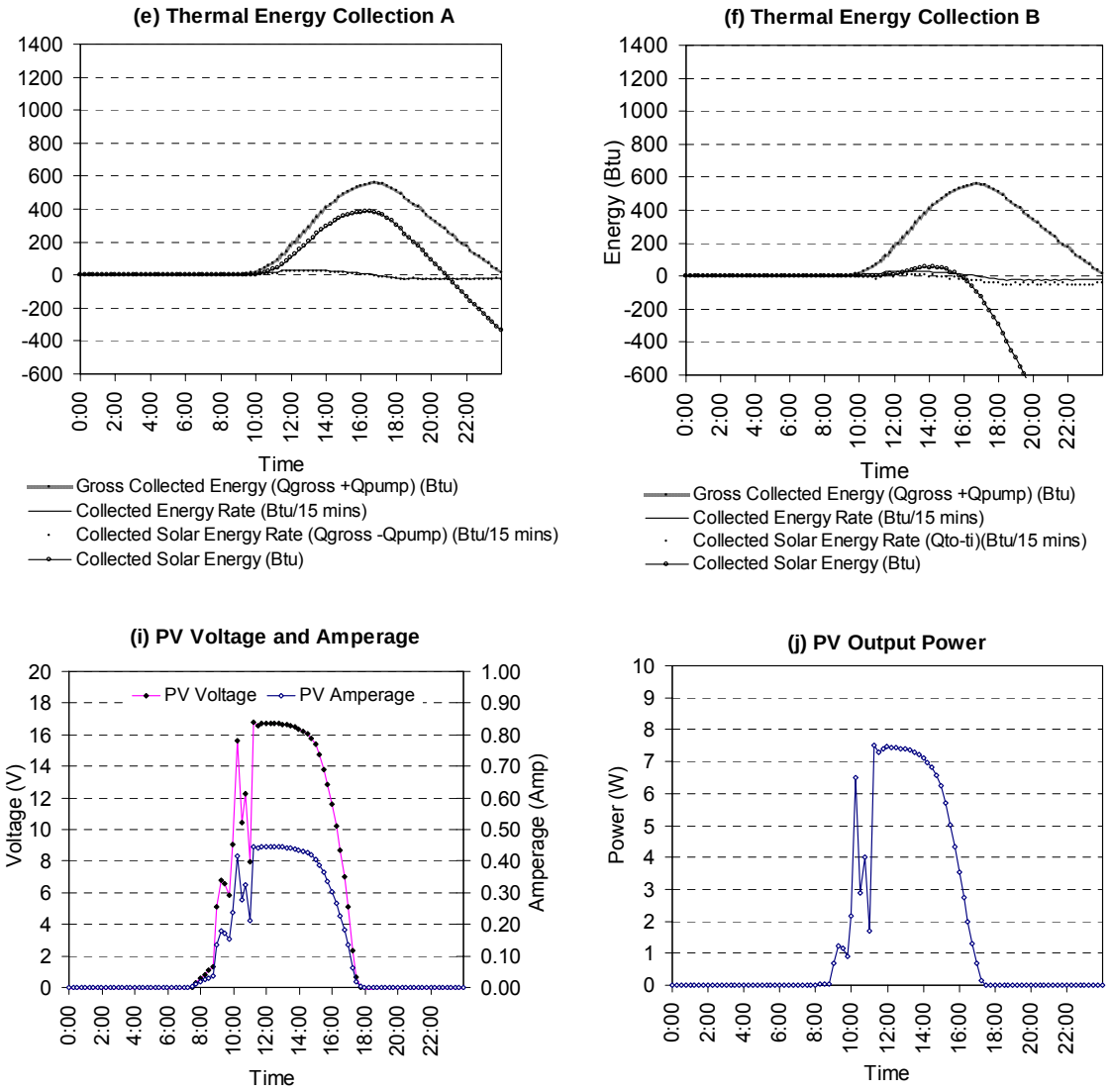


Figure B.9 *Results (e-j) from Day Mode Experiment on January 6, 2003.*

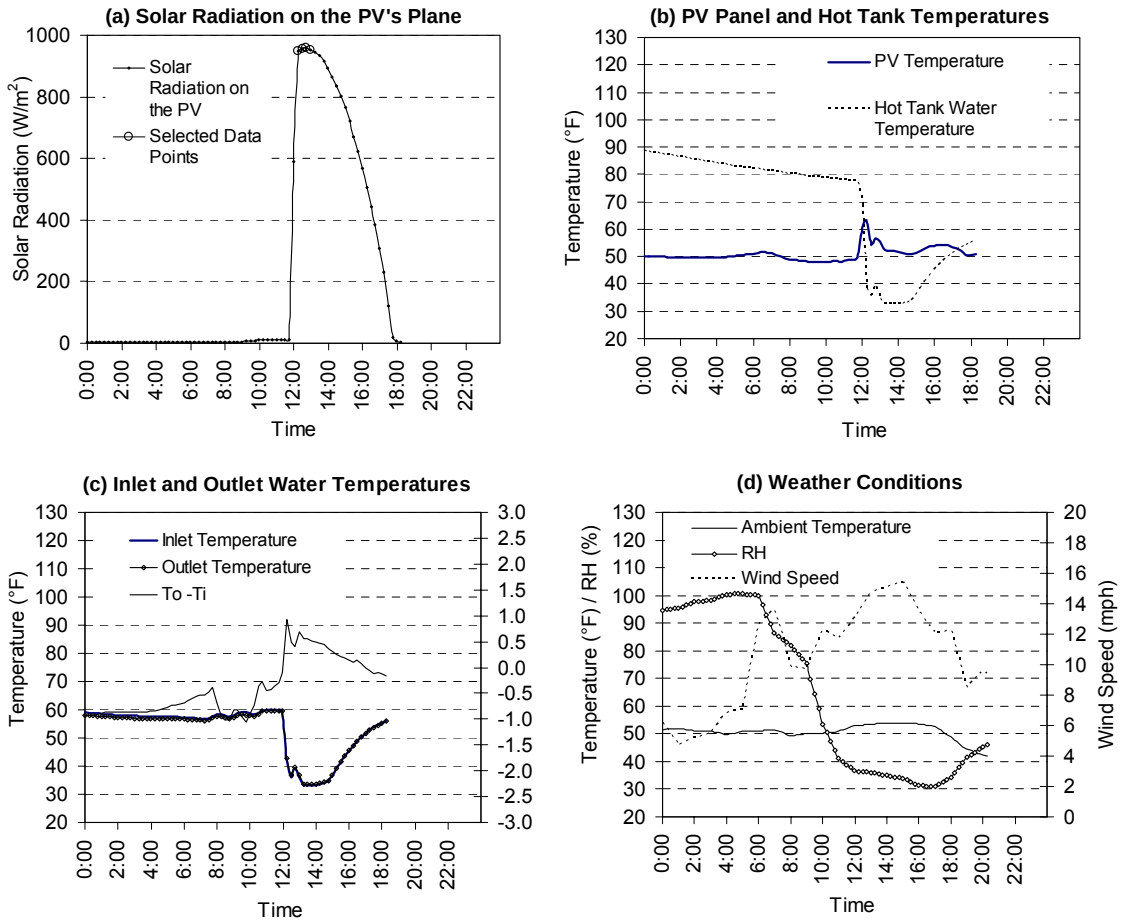


Figure B.10 *Results (a-d) from Day Mode Experiment on January 16, 2003.*

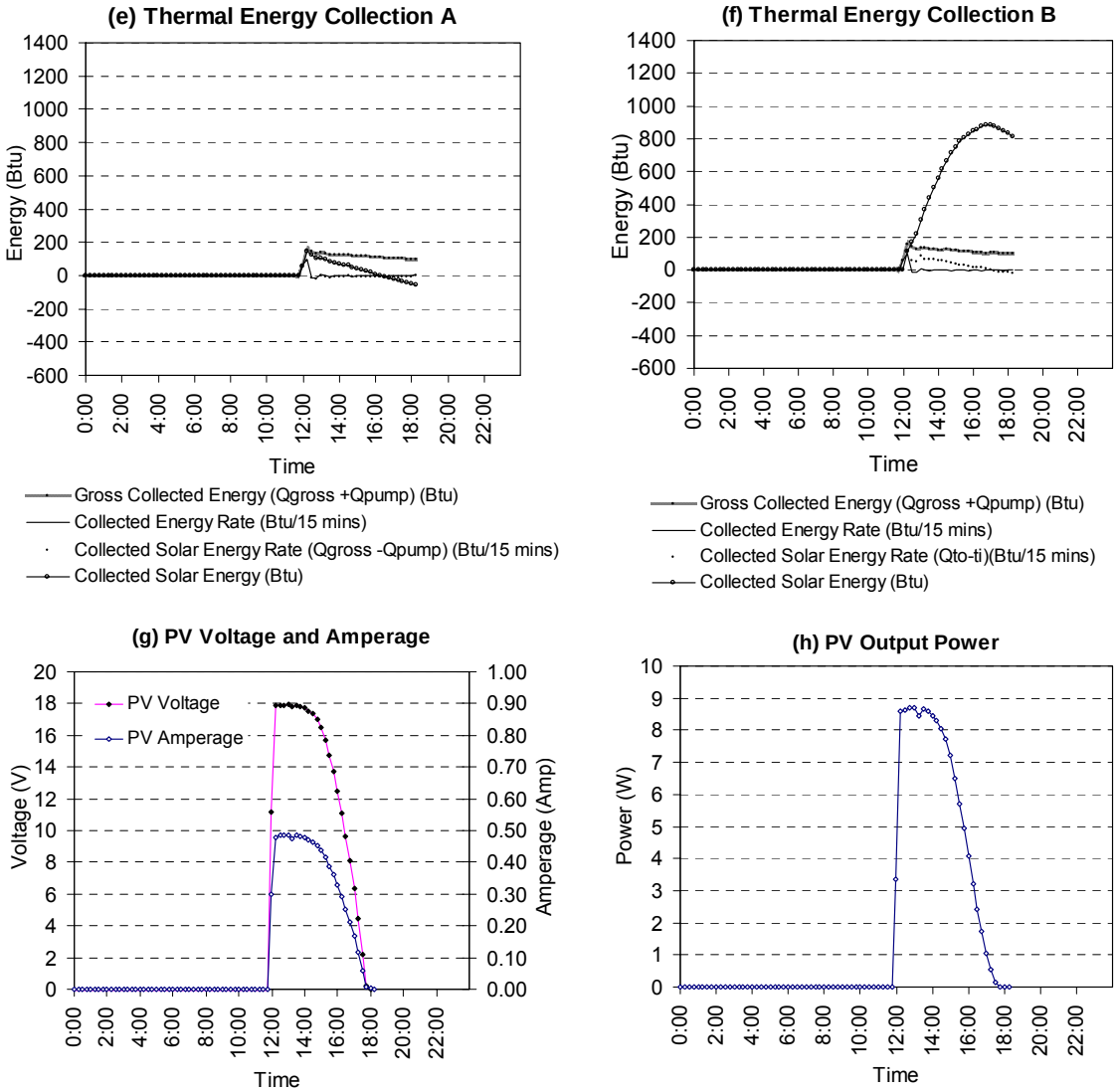


Figure B.11 *Results (e-j) from Day Mode Experiment on January 16, 2003.*

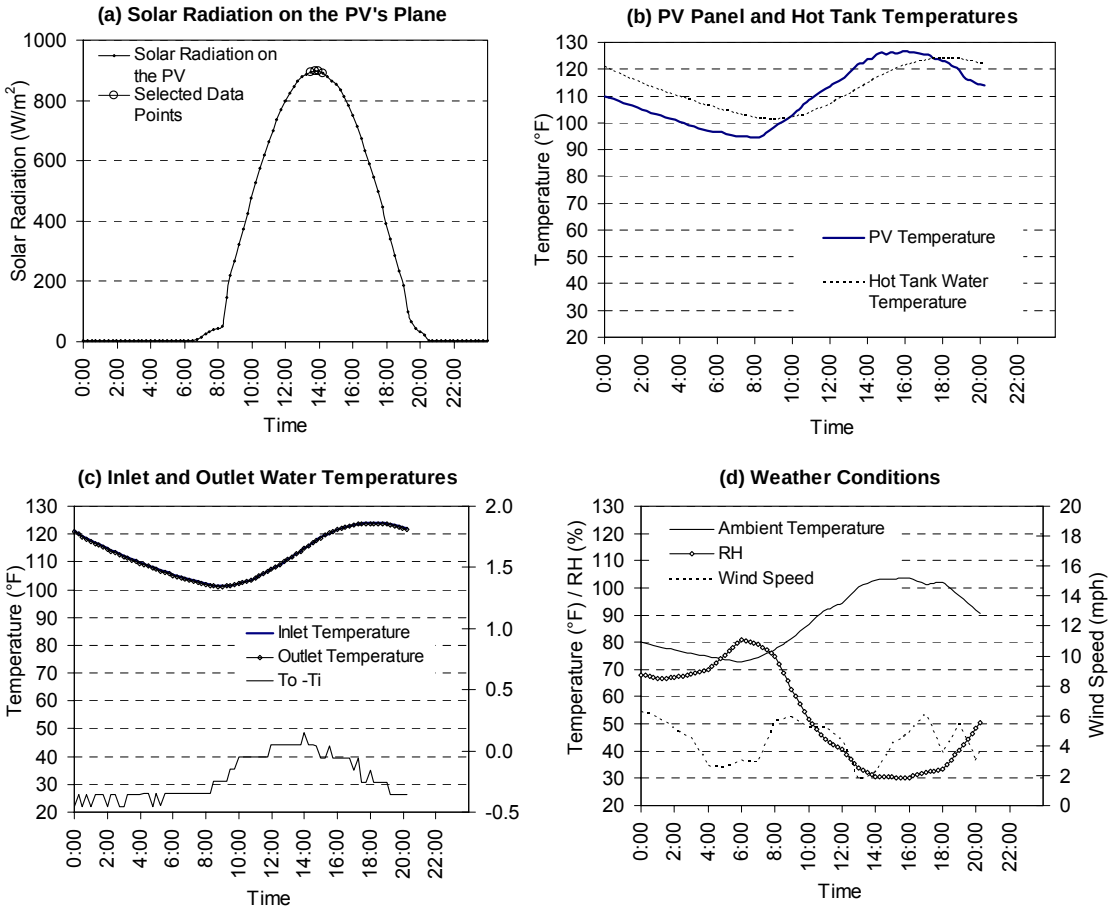


Figure B.11 *Results (a-d) from Day Mode Experiment on May 31, 2003.*

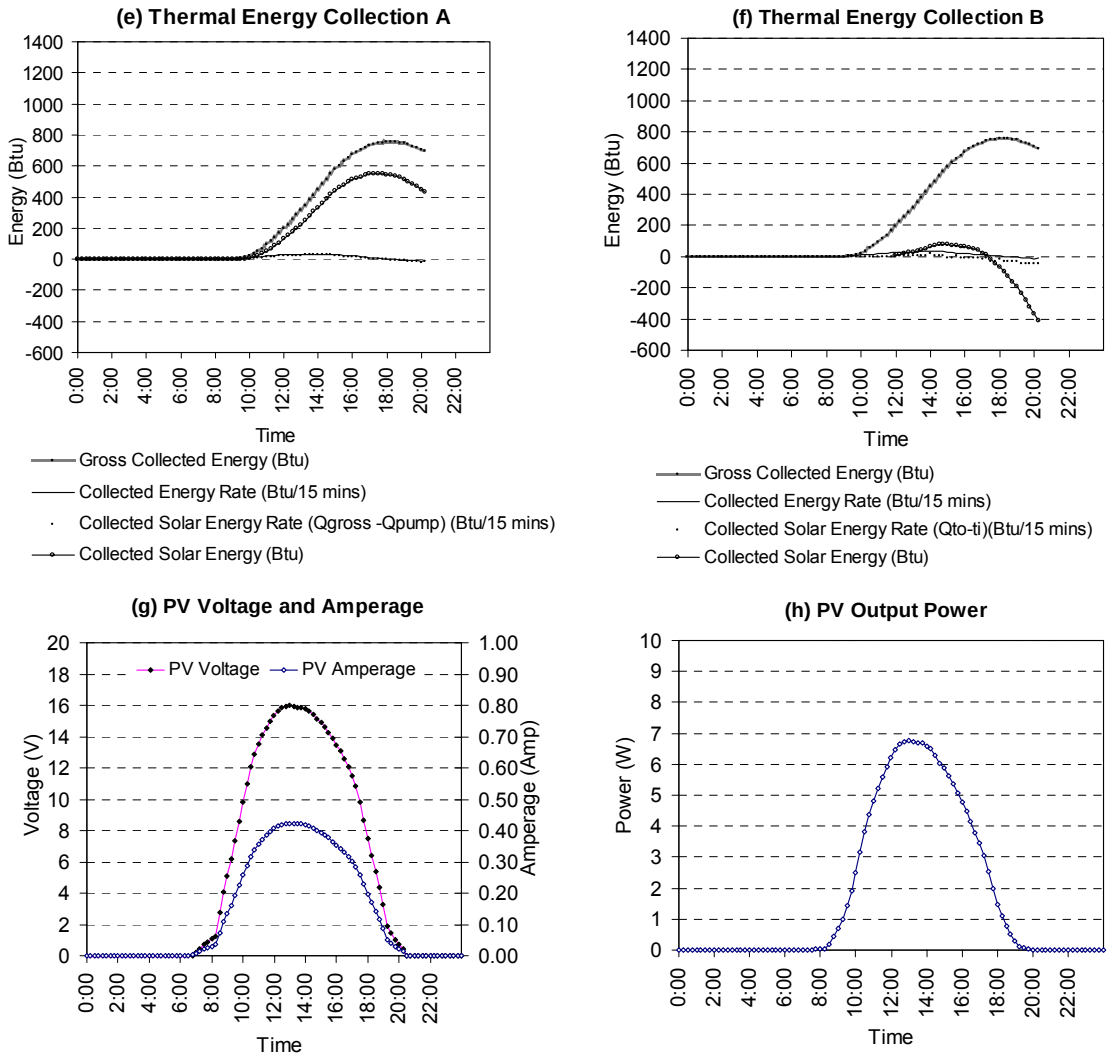


Figure B.12 *Results (e-h) from Day Mode Experiment on May 31, 2003.*

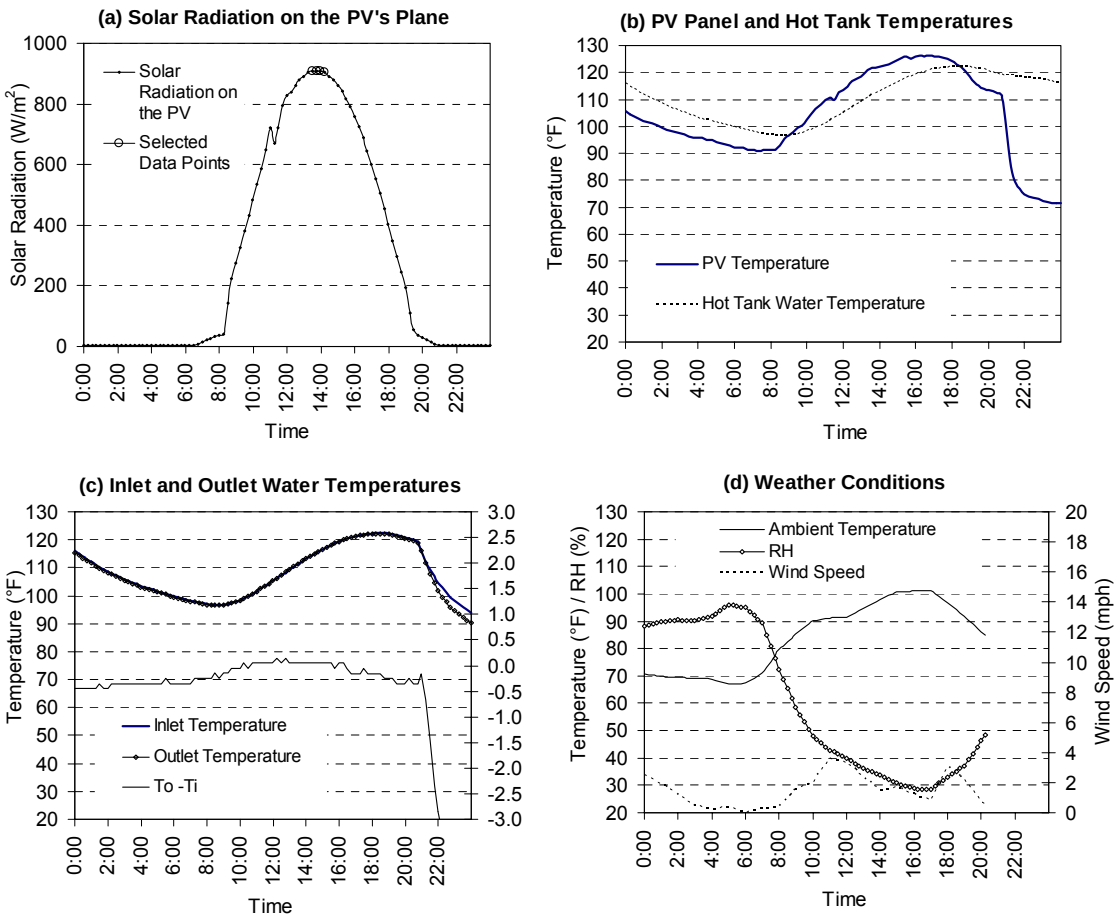


Figure B.13 *Results (a-d) from Day Mode Experiment on June 7, 2003.*

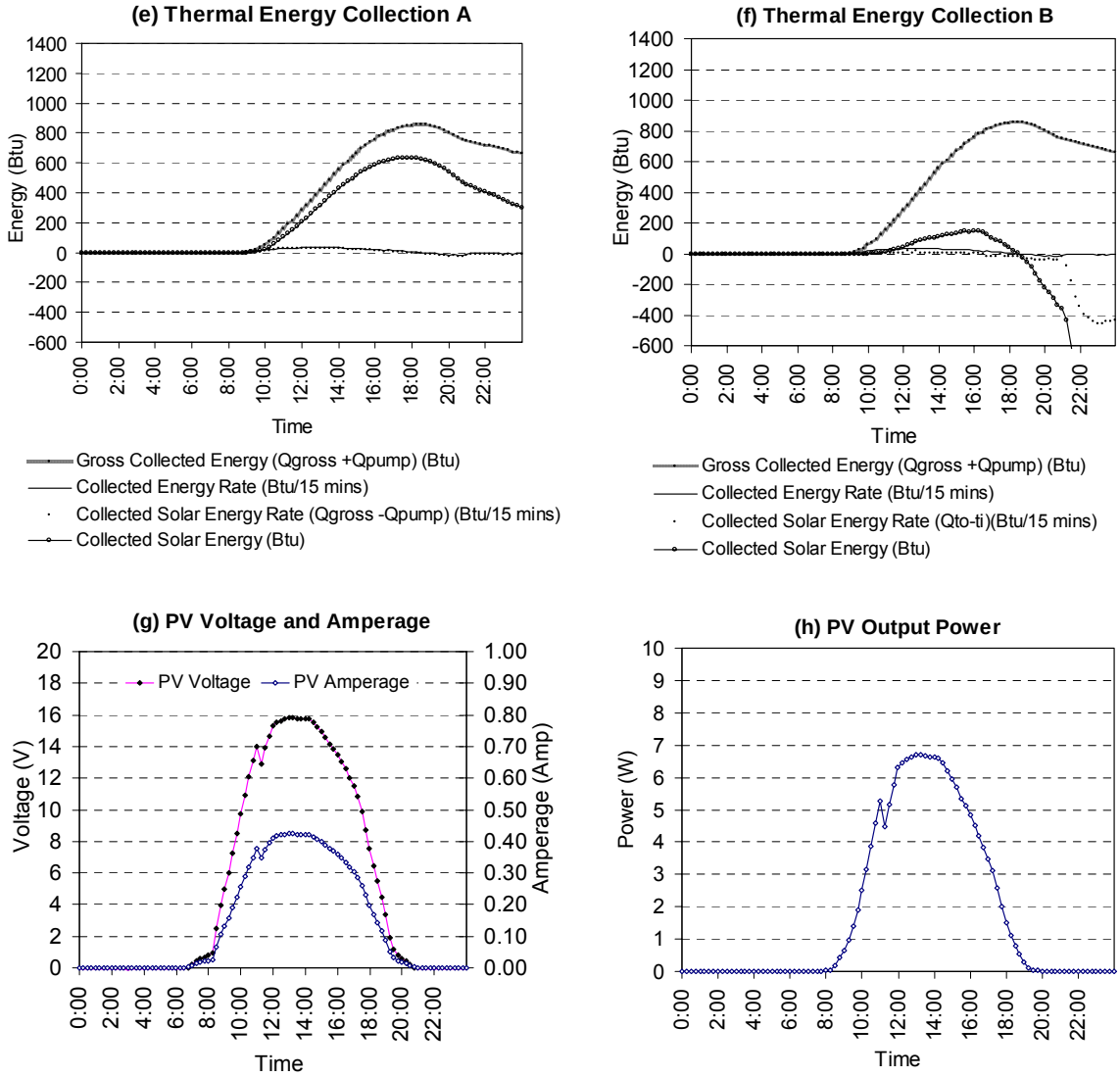


Figure B.14 *Results (e-h) from Day Mode Experiment on June 7, 2003.*

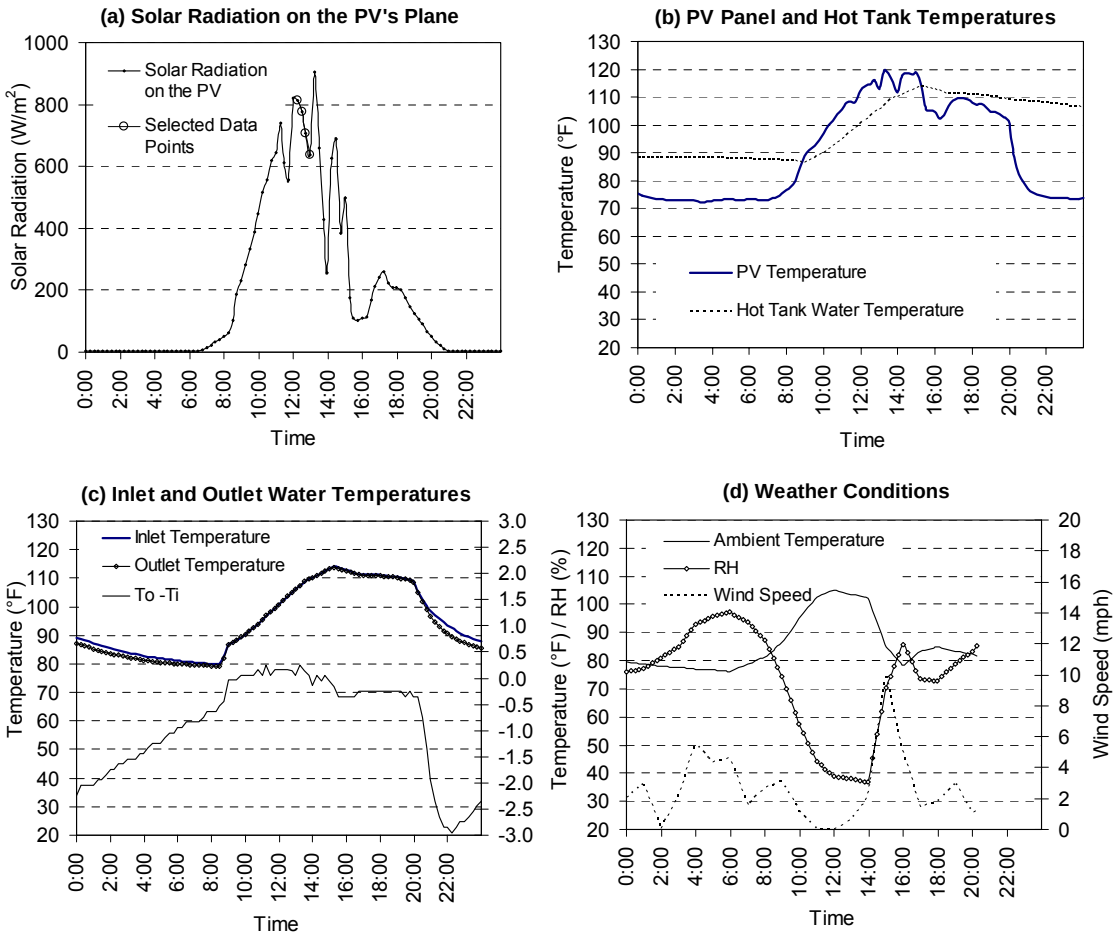


Figure B.15 *Results (a-d) from Day Mode Experiment on July 3, 2003.*

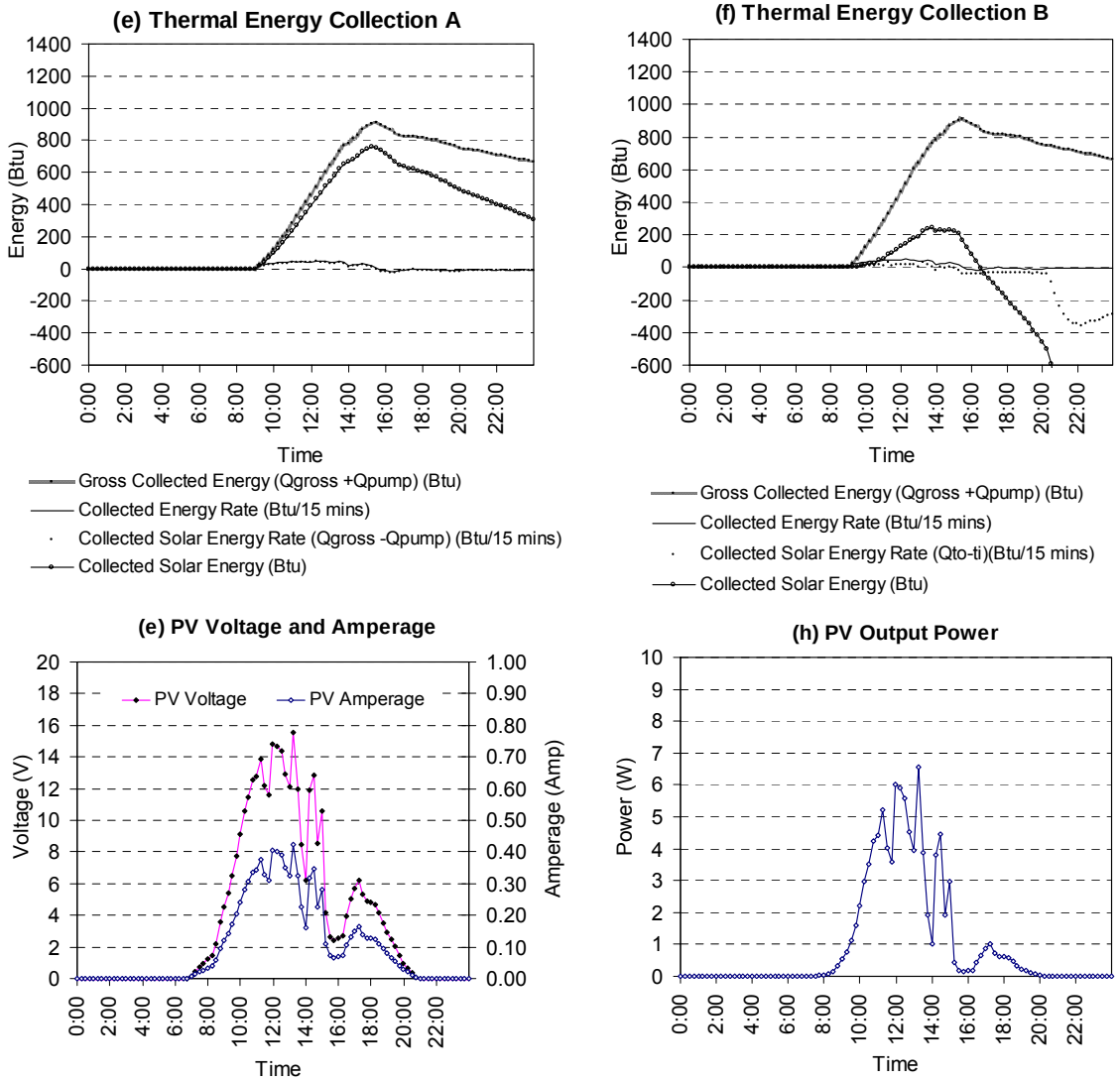


Figure B.16 *Results (e-h) from Day Mode Experiment on July 3, 2003.*

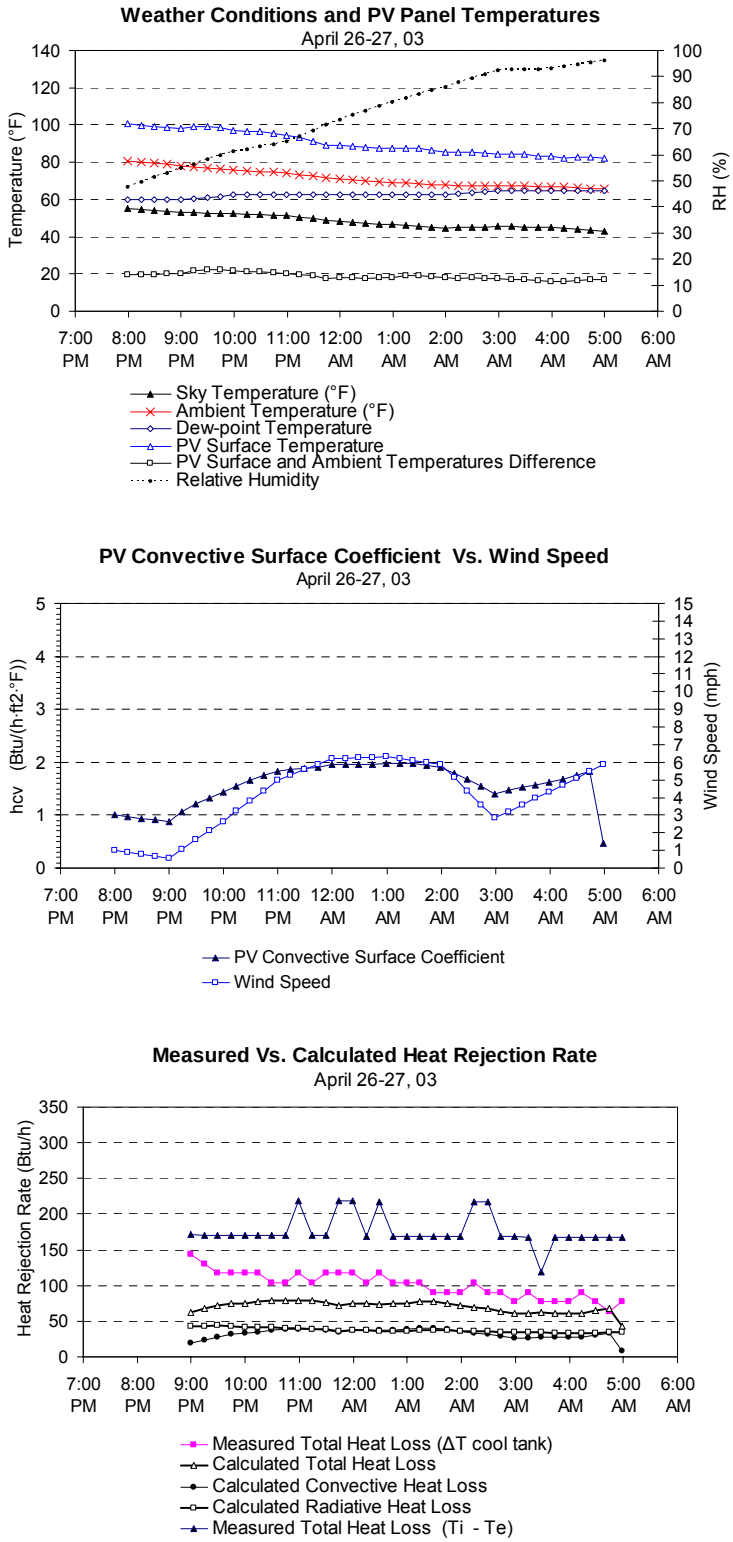


Figure B.17 *Results from Night Mode Experiment on April 26-27, 2003.*

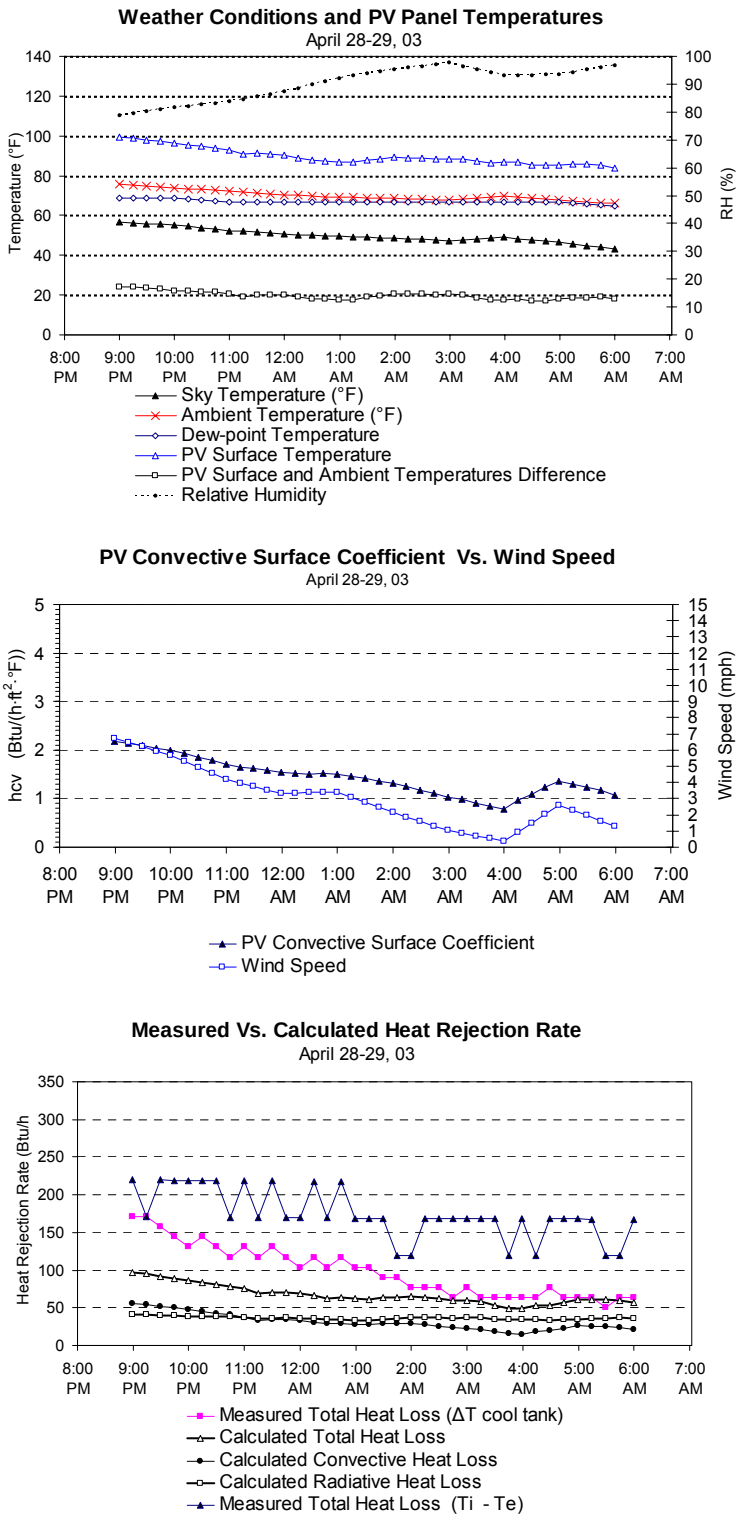


Figure B.18 *Results from Night Mode Experiment on April 28-29, 2003.*

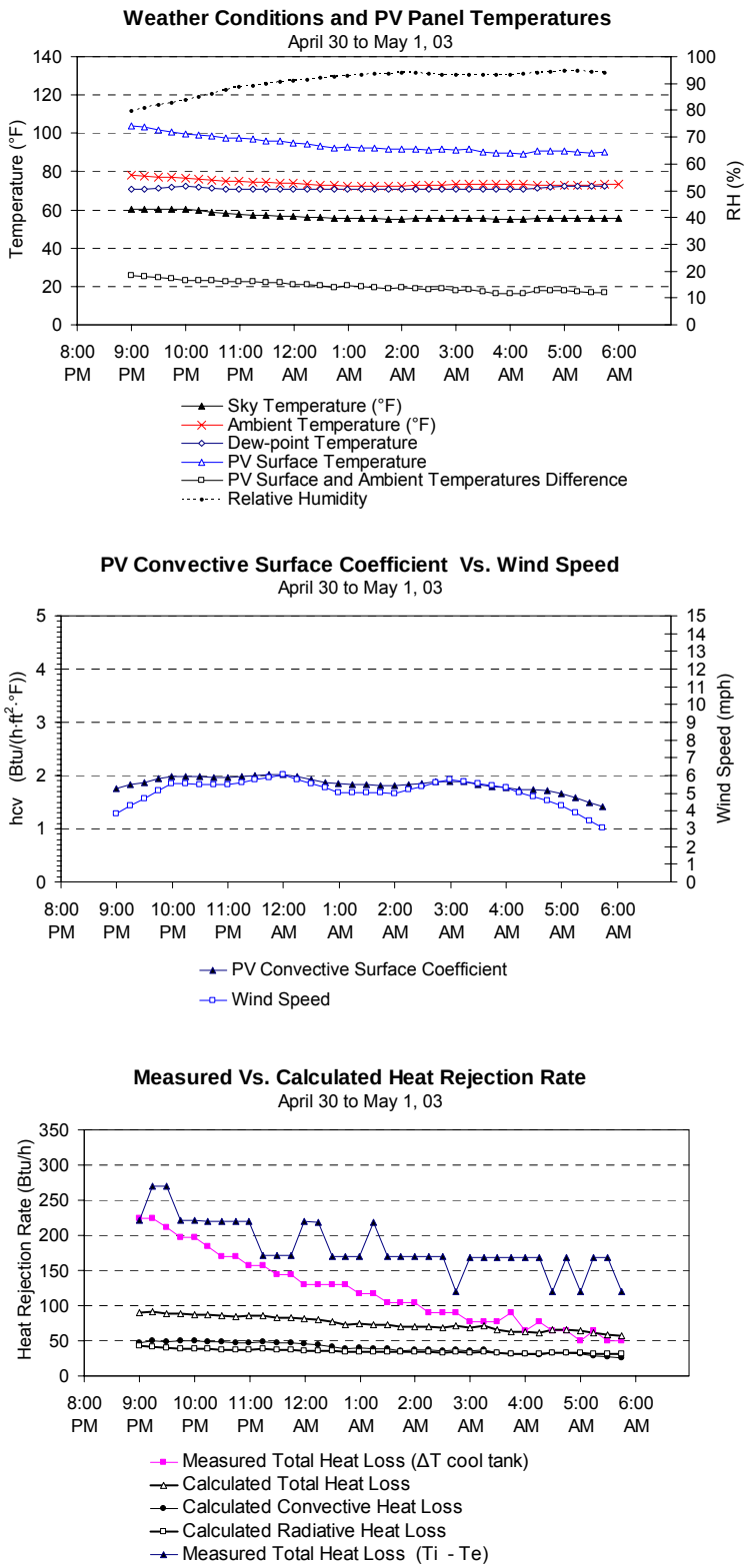


Figure B.19 *Results from Night Mode Experiment on April 30 to May 1, 2003.*

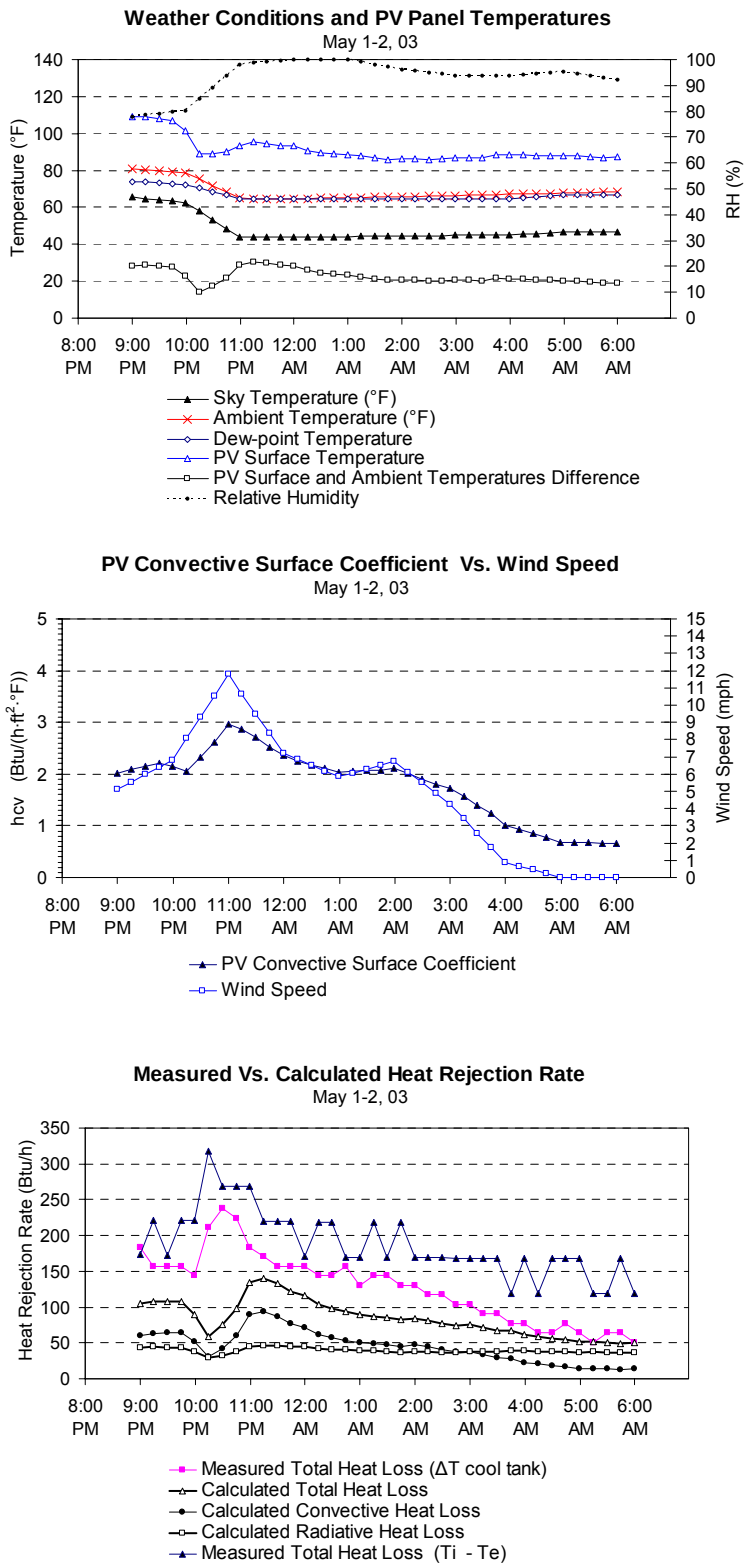


Figure B.20 *Results from Night Mode Experiment on May 1-2, 2003.*

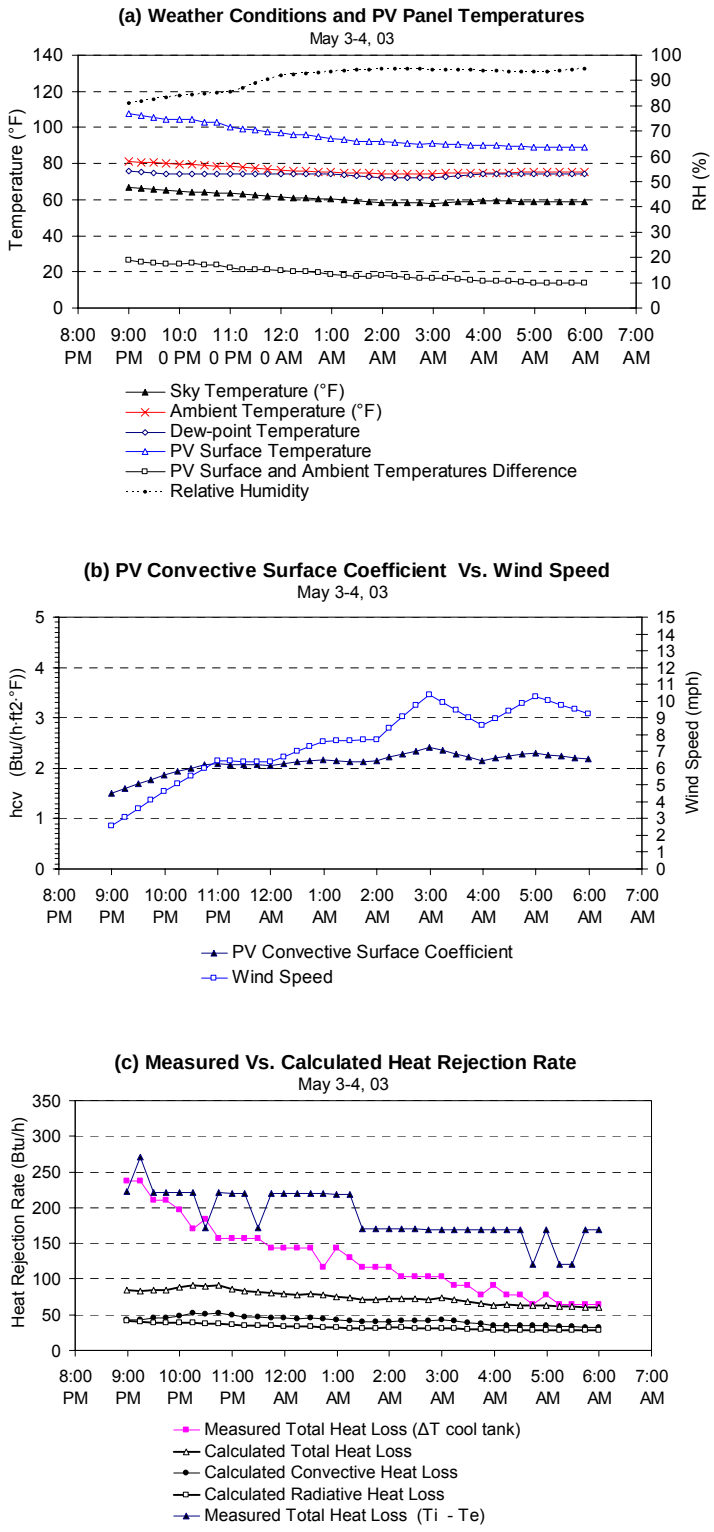


Figure B.21 *Results from Night Mode Experiment on May 3-4, 2003.*

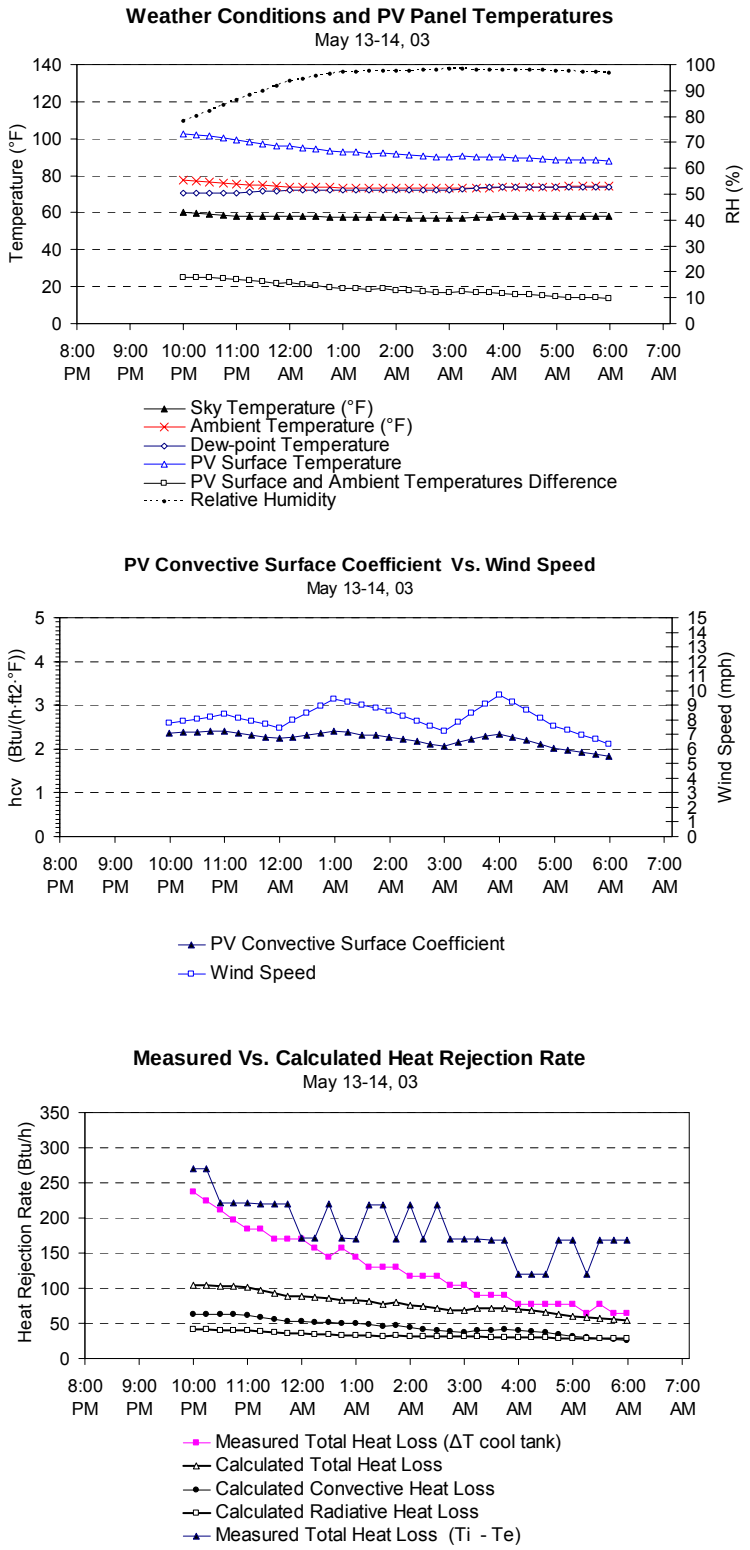


Figure B.22 *Results from Night Mode Experiment on May 13-14, 2003.*

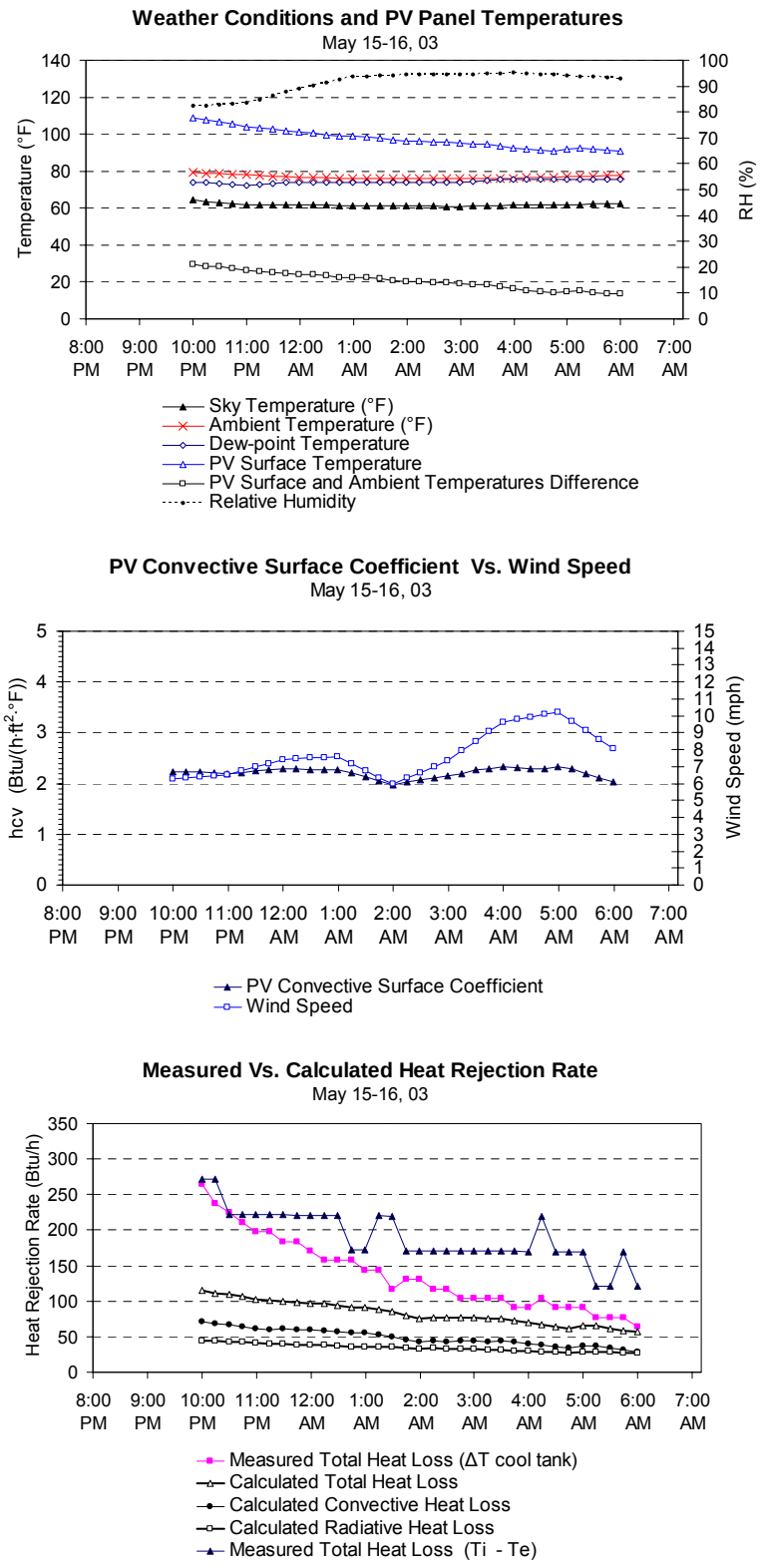


Figure B.23 *Results from Night Mode Experiment on May 15-16, 2003.*

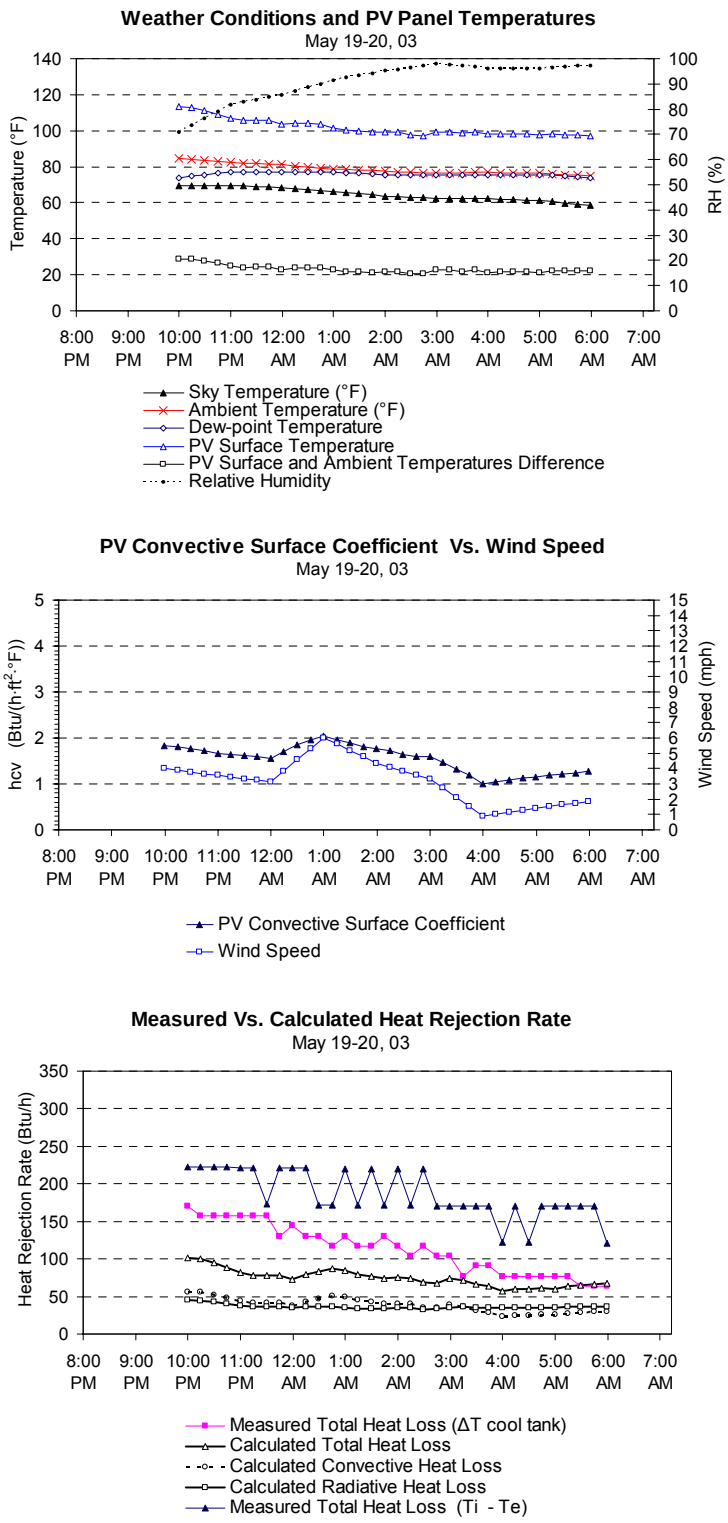


Figure B.24 *Results from Night Mode Experiment on May 19-20, 2003.*

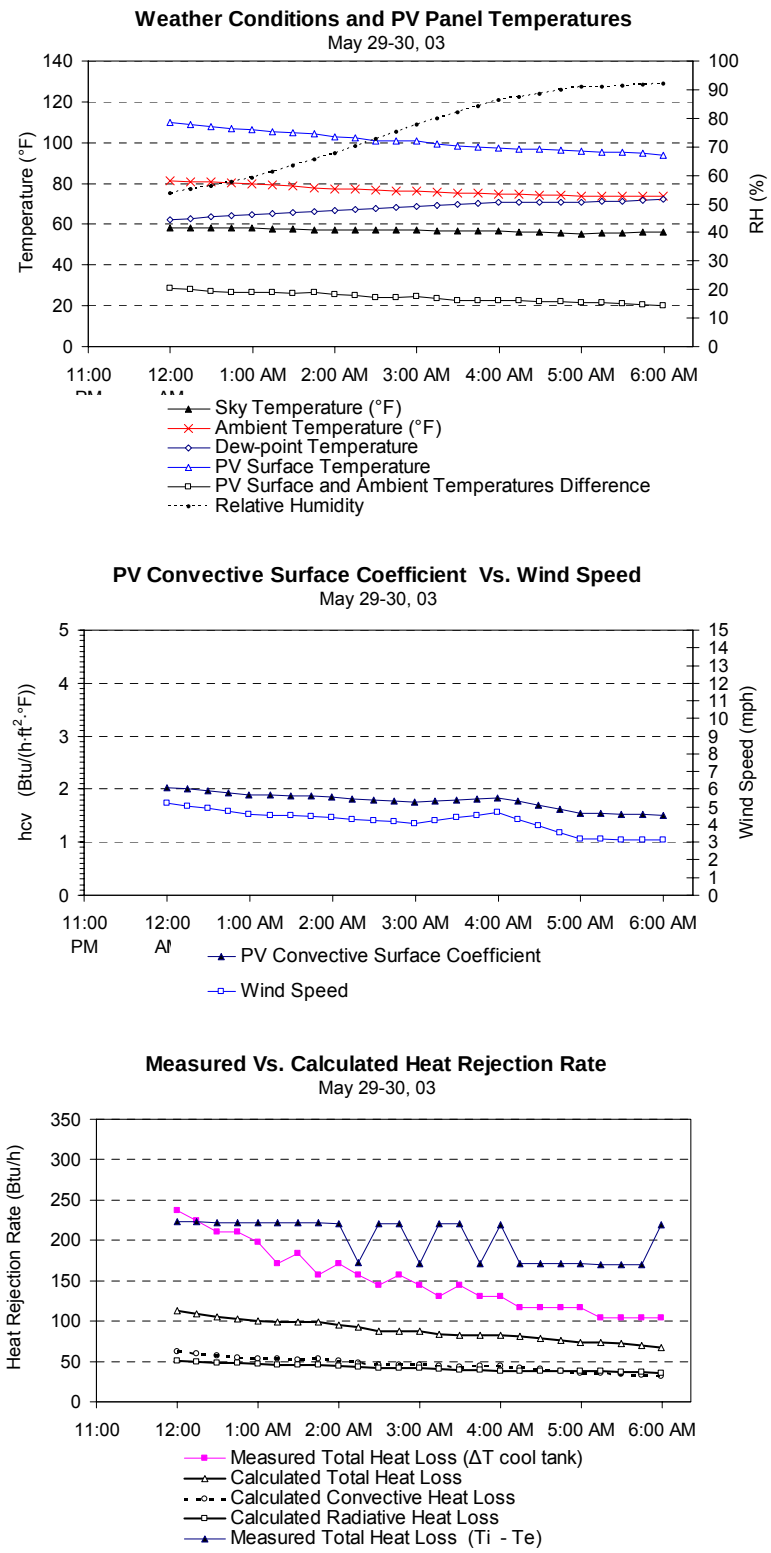
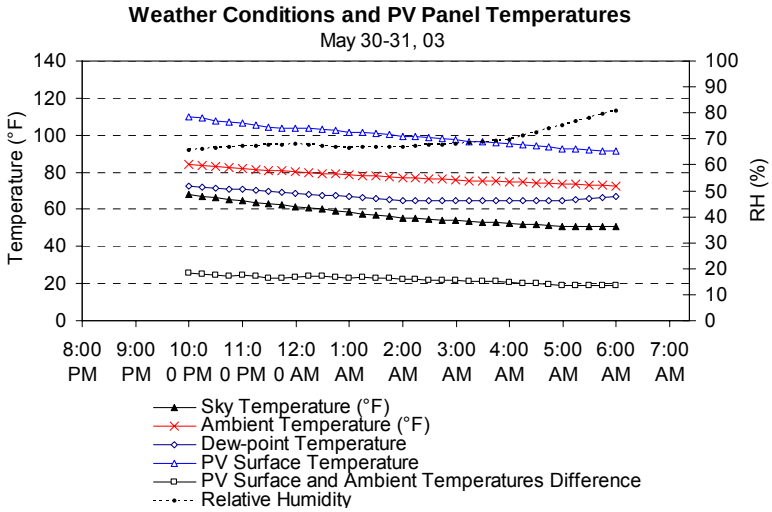
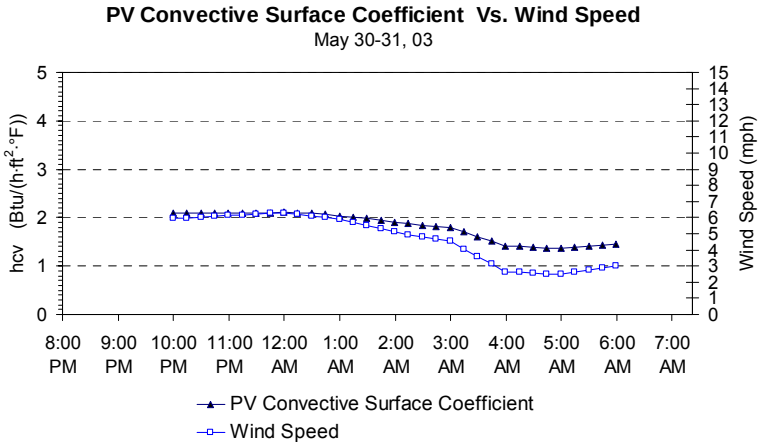


Figure B.25 *Results from Night Mode Experiment on May 29-30, 2003.*





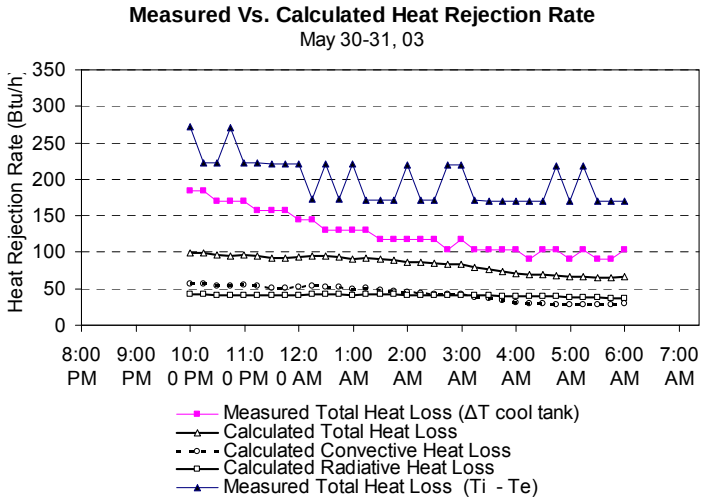


Figure B.26 *Results from Night Mode Experiment on May 30-31, 2003.*

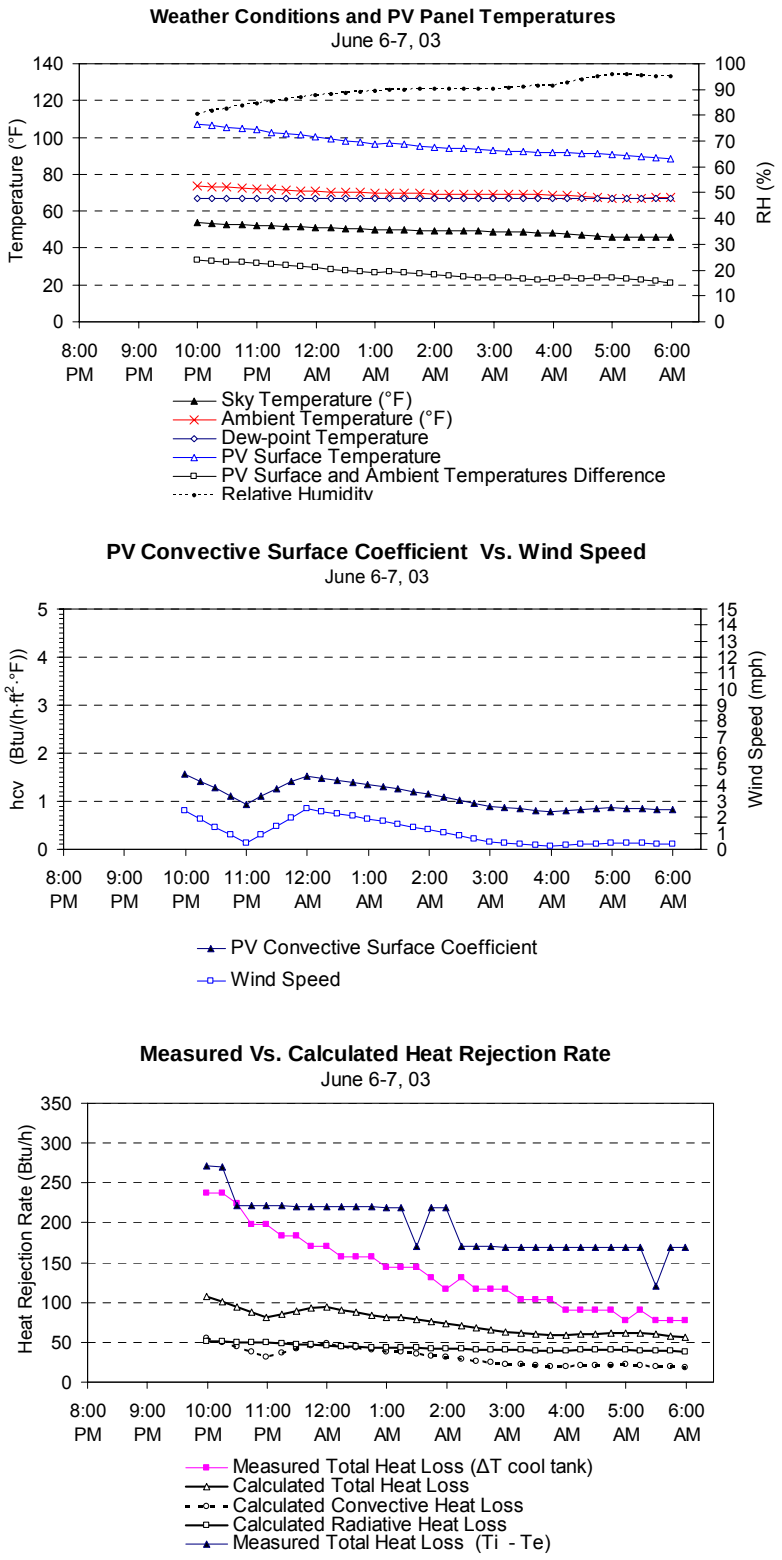


Figure B.27 *Results from Night Mode Experiment on June 6-7, 2003*

B.5 Anti-freezing Mode Diagram

An anti-freezing mode was used to prevent the damage that could occur to the PV-T^2 panel and the piping system due to the freezing water. The system was switched to the anti-freezing mode in very cool days/nights (when the ambient air temperature was lower than 40 ^oF), which occurred during the winter. Figure B.28 shows the anti-freezing mode diagram. In Figure B.28, there are three extra equipments that need to equip to the system to protect the water in the PV-T2 panel and the piping system from freezing: 1) Insulated cover for the PV-T^2 panel, 2) Two four-foot water hoses, 3) Foam insulation (Polystyrene) to cover the radiator's inlet and outlet air ducts.

As shown in the Figure B.28, the anti-freezing mode consists of two independent piping loops: 1) PV-T^2 panel loop, 2) Radiator loop. The PV-T^2 panel loop was to prevent freezing water occurred in the PV-T^2 panel and the exterior pipes/tubes that connect to the panel. The loop was operated by pumping water in the Cool tank to the water heater, and then the heated water was circulated through the PV-T^2 panel, which was covered with the insulated cover, by piping system and the extra water hoses. Then, from the PV-T^2 panel, the heated water drained back to the Cool tank. For the Radiator loop, this loop was to prevent freezing water occurred in the radiator that has inlet and outlet air ducts extended to the exterior. The inlet and outlet air ducts were insulated with form insulation (polystyrene). The water in the hot tank was pumped to the radiator, and drained back to the hot tank. Although the water in this loop was not heated by the water heater as the water in the PV-T^2 panel loop (due to the difficulty of pipes and water hose connection), the light bulb was also turned on in the anti-freezing mode to warm the interior air, so the radiator was also warmed by the heat from the light bulb. The heat from the light bulb and the heat contributed from the pump were proved to be sufficient to prevent the water in the radiator from freezing. The circulation of water in the two loops continued until the system was shut off when the ambient temperature was above 40 ^oF.

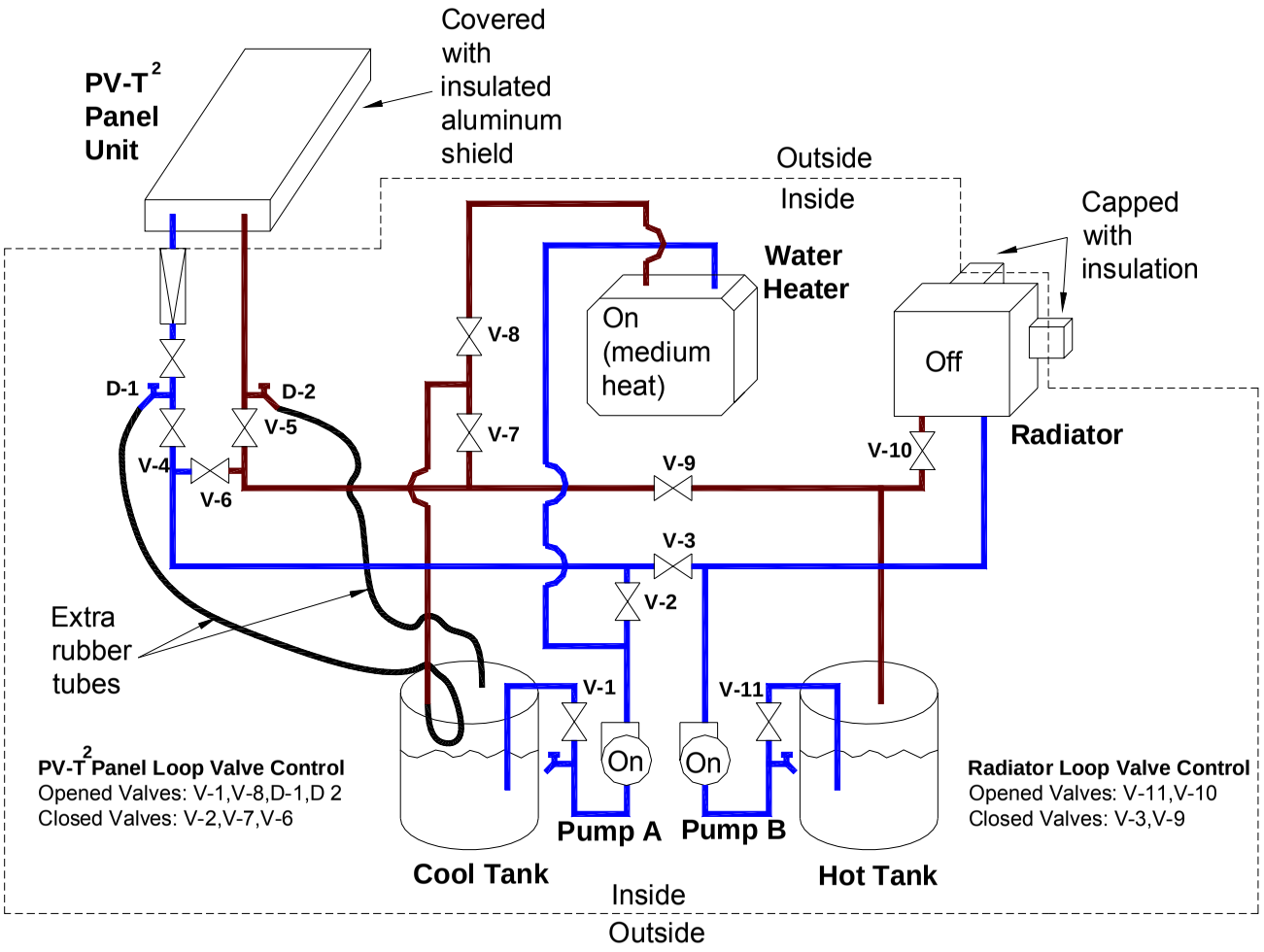


Figure B.28 *Anti-Freezing Mode Diagram. There are two water circulating loop: PV-T2 panel Loop (shown on the left side of the diagram) and Radiator Loop (shown on the right side).*

B.6 Null Test: Heat Gain from the Pump

A null test was conducted in order to measure the heat gain rate that was contributed from the pump. The method was circulating water from a tank through a small piping loop inside the experiment box. The box and the pipes were well insulated, so the only one heat source is from the pump. The water in the cool tank was pumped by Pump A and circulated through the water heater that is turn off, and circulated back to the cool tank. The duration of the test was approximately thirteen hours. Temperature of water in the hot tank was measured and recorded by the data logger. Figure B.29 shows the energy gain rate from the pump and gross collective energy from the pump.

From Figure B.29, in the first three hours, energy gain from the pump was relatively high (16-70 – 23.38 Btu/15 min). The energy gain from the pump was declined to a range of 3.43 to 6.68 Btu/15 min from minute 600th to minute 800th. The energy gain rate in this period was relative stable, so the averaged pump heat gain was calculated from this period which was 5.94 Btu/15 min.

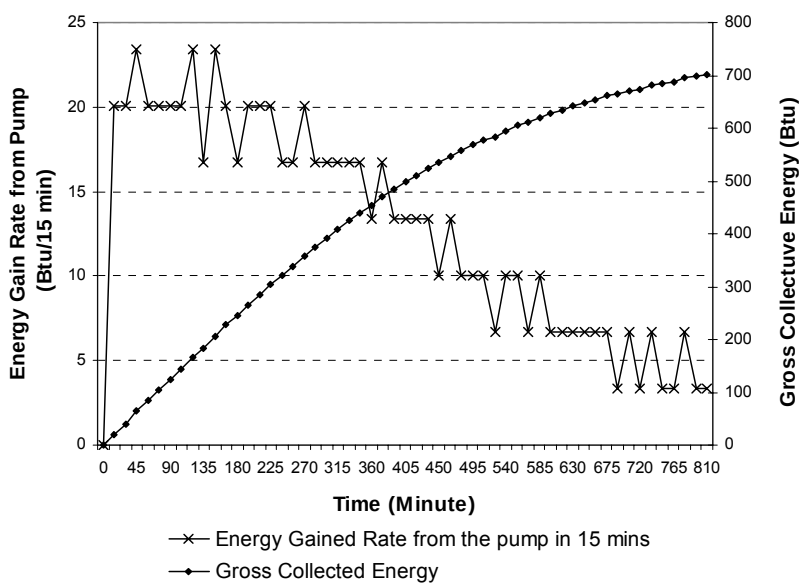


Figure B.29 *Results from the Null Mode Experiment. The graph shows the rate of heat from the pump contributed to the system.*

APPENDIX C

CALIBRATION OF MEASURING DEVICES

C.1 Calibration of Devices Used in the Case-Study House

Portable data loggers were used to measure the temperature and humidity of the case-study house. Temperature sensors were calibrated with a calibrated Type-T thermocouple. The thermocouple was calibrated with ice-point and water boiling-point temperatures (Wise, 1986; ASTM E 563-97). Distilled water was used to make ice and boiling water. Calibration of the humidity sensors used a method of humidity control by chemical systems that were described by Greenspan (1976).

Figure C.1 shows temperatures measured by the portable data loggers or “Hobos” # 1 to # 4 versus reference temperatures measured by a calibrated thermocouple. The portable data loggers and the calibrated thermocouple were placed together in a refrigerator that was used for instrument calibration. Three point temperatures calibration was performed. The refrigerator temperature was controlled by adjusting its thermostat for below freezing point and cool temperature measurements, and by turning it off for room temperature measurement. Figure C.2 shows temperatures measured by the portable data loggers after they were calibrated versus the reference temperatures.

There were three humidity sensors in those four potable data loggers (Hobo# 4 was used to measure only temperatures). Humidity calibrations of the three portable data loggers were performed by placing all data loggers in a small glass container. Three saturated salt solutions, which were Lithium Chloride, Magnesium Chloride, and Sodium Chloride, were used to generate constant relative humidities which occurred in the air above these solutions in a small container. In the container, constant relative humidities of approximately 11 percent, approximately 32 percent, and approximately 75 percent were generated by Lithium Chloride, Magnesium Chloride, and Sodium Chloride, respectively. Each of the saturated salt solutions was put in the container where the data loggers were positioned to stay above the solutions. The data loggers were set to measure both temperature and humidity. A calibrated RTD thermometer connected with a data logger was used to measured air temperature in the container. Figure C.4 shows the calibration of the RTD thermometer which was calibrated with

ice-point and water boiling-point temperatures (Wise, 1986). The container, then, was put a refrigerator. For each of saturated salt solutions, the temperature of the refrigerator was adjusted to three different temperature conditions (low temperature, room temperature, and high temperature). The refrigerator's thermostat was adjusted to low temperature position in the case of the low temperature measurement. The refrigerator was turned off in the case of room temperature measurement. A 60W incandescent lamp was put in the refrigerator (with the refrigerator turned off) to create a high temperature condition in the refrigerator. In this high temperature condition, the refrigerator's door was not completely closed because the air temperature in the refrigerator could be extremely high and not constant. Thus, this condition should be avoided. Reference humidities in those conditions of each salt were calculated be by using temperatures measured by the RTD (Greenspan, 1976). The results of the humidity calibration of the portable data loggers are presented in Figure C.3.

.

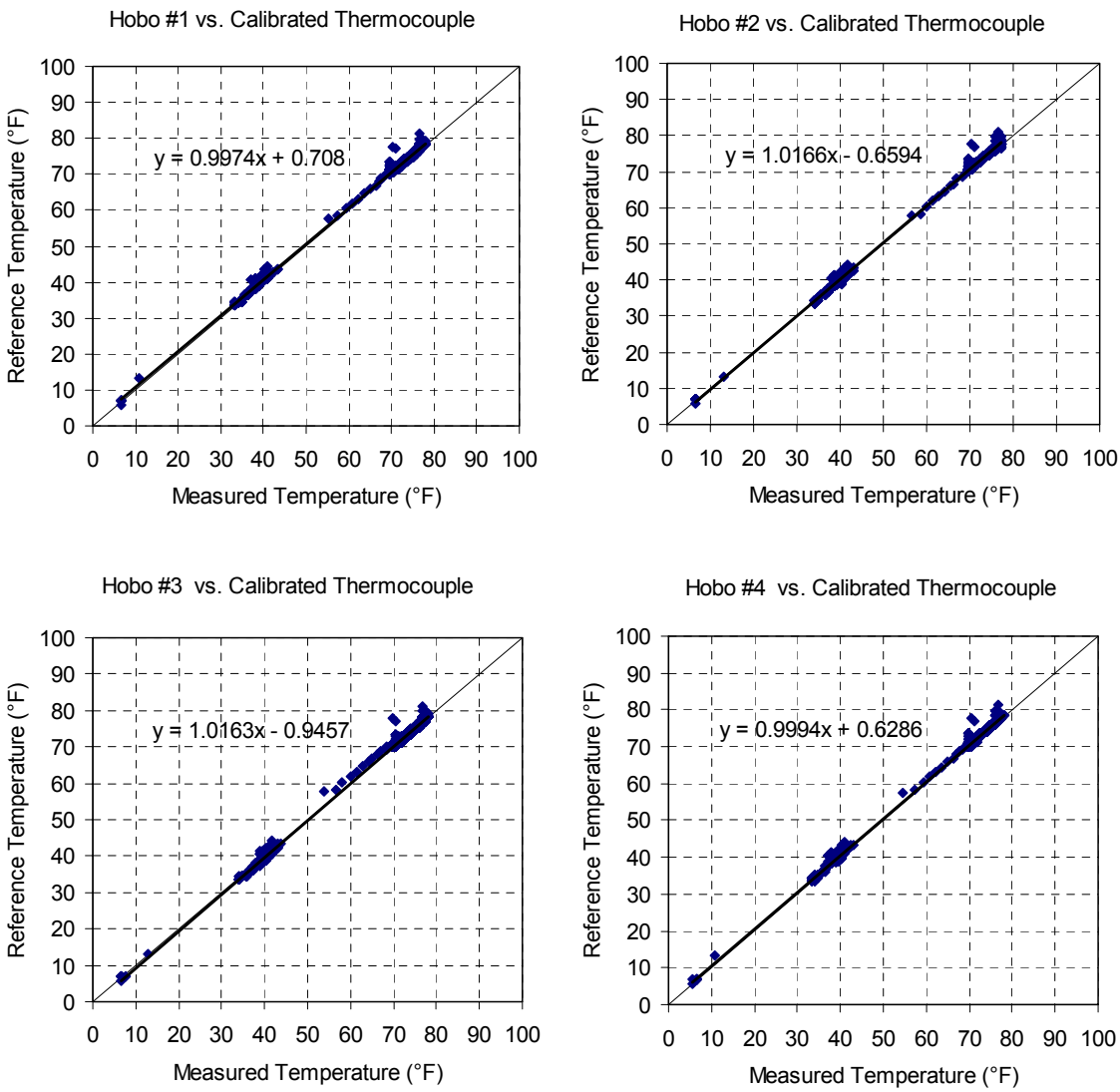


Figure C.1 *Temperatures Measured by Portable Data loggers versus Temperatures Measured by a Reference Thermometer.*

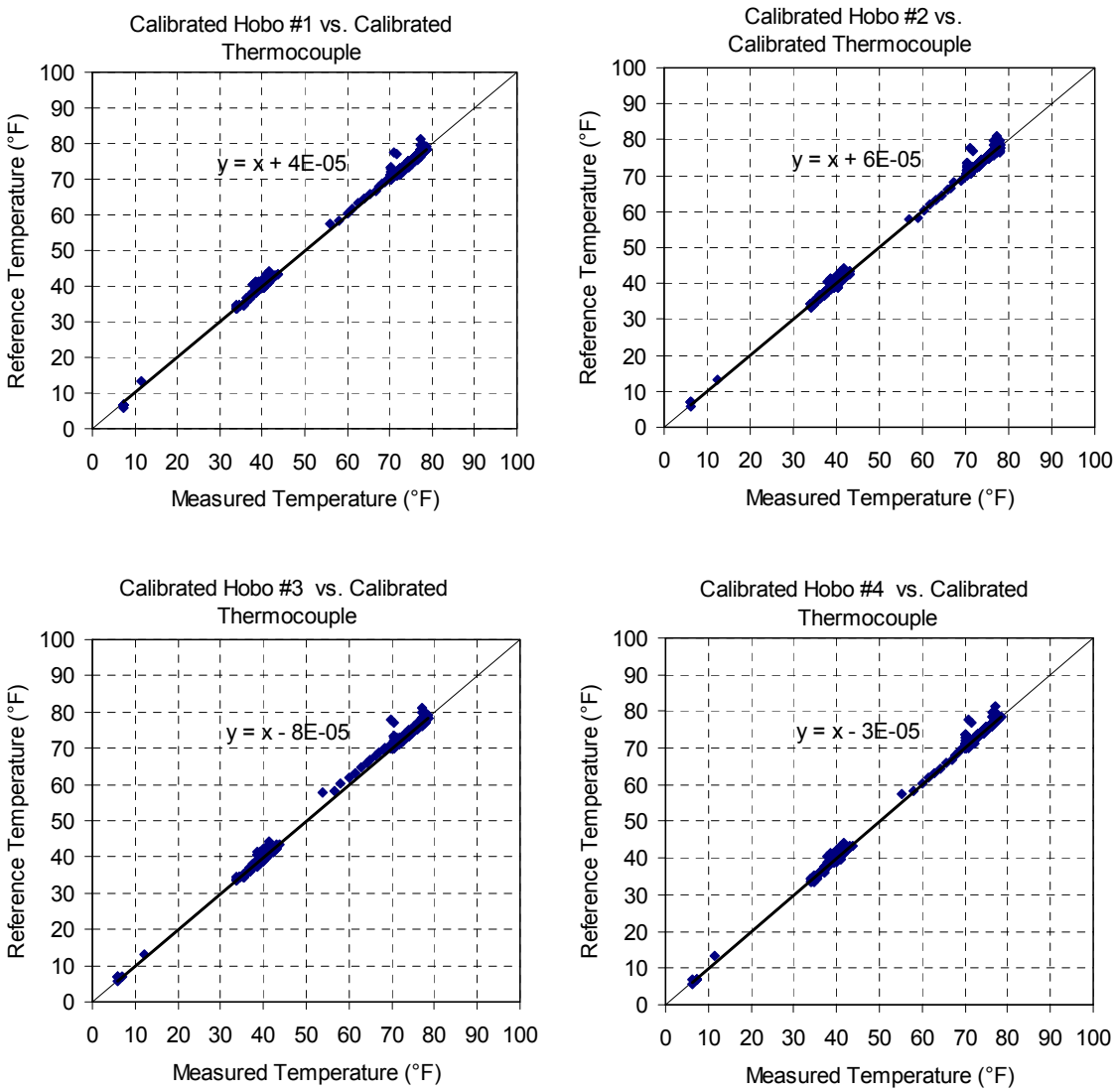


Figure C.2 *Calibrated Temperatures Measured by Portable Data loggers versus Temperatures Measured by a Reference Thermometer.*

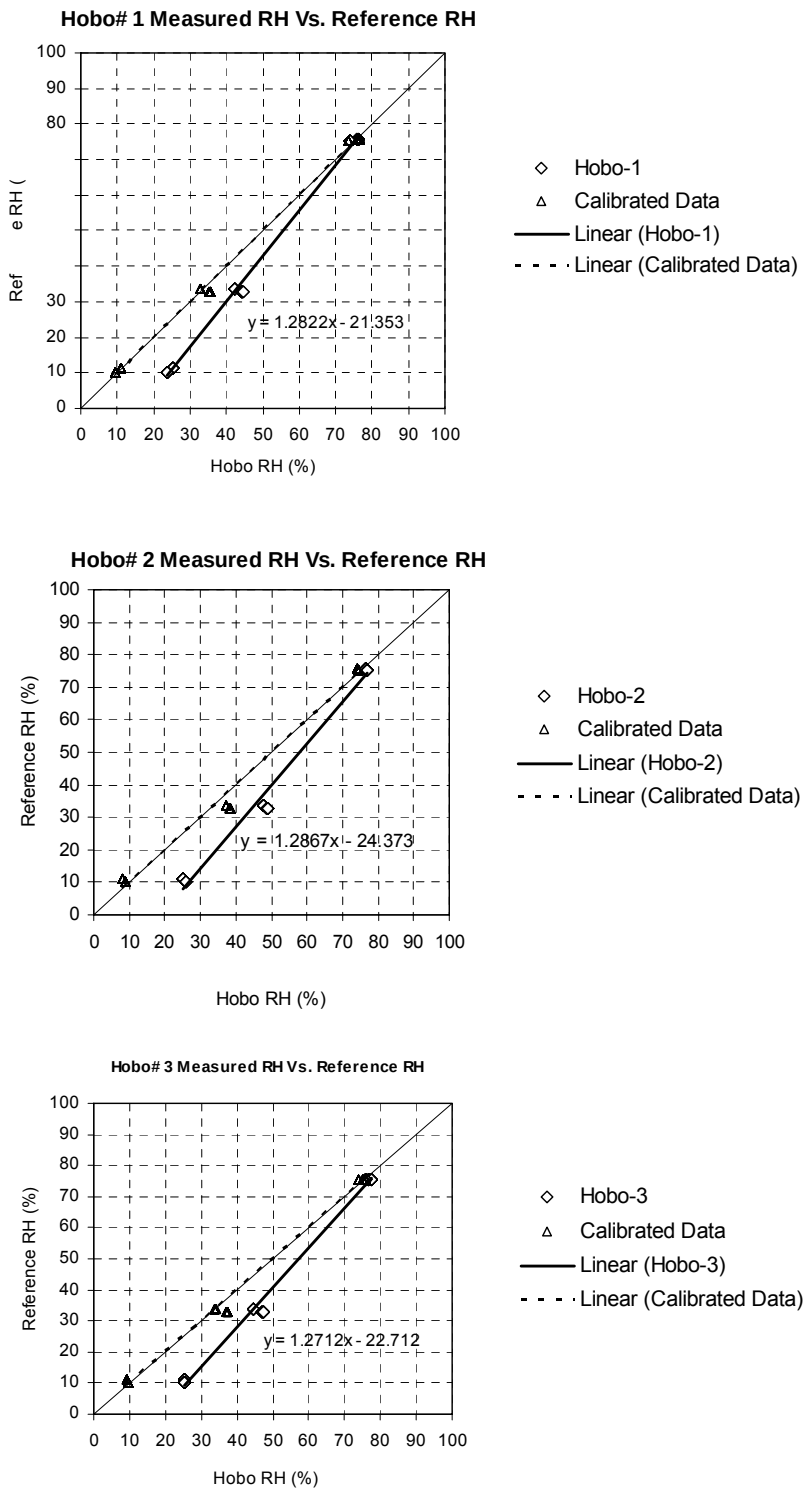


Figure C.3 *Humidity Calibrations of The Portable Data Logger. From Top to bottom: Hobo#1, Hobo#2 and Hobo#3.*

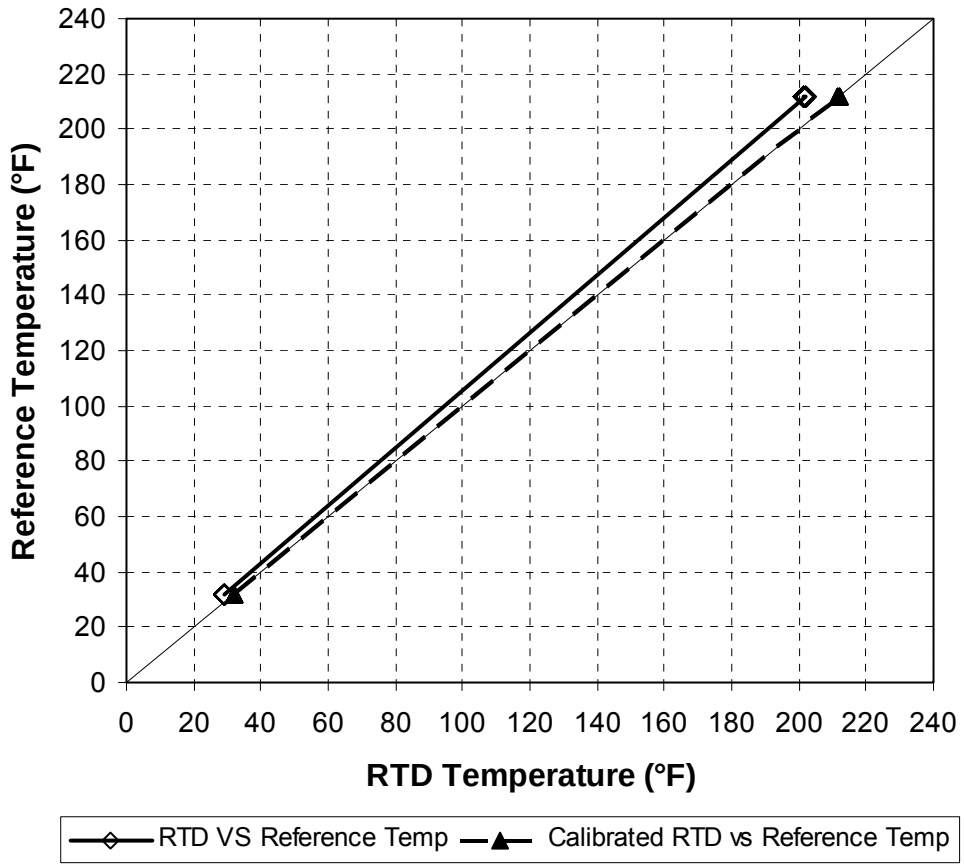


Figure C.4 *Temperature Calibration of The RTD Thermometer.*

C.2 Calibration of Devices Used in the Hybrid PV-T Experiment

C.2.1 Instruments Used for Measuring Temperature

Liquid-in-glass thermometer, Type T thermocouples, portable data loggers were used for measuring temperature in the research. Liquid-in-glass thermometer and Type T thermocouples were calibrated with ice-point and water boiling-point temperatures (Wise, 1986; ASTM E 563-97). The calibration of the thermocouples is showed in Figure C.5. The calibration of the liquid-in-glass thermometer is showed in Figure C.6.

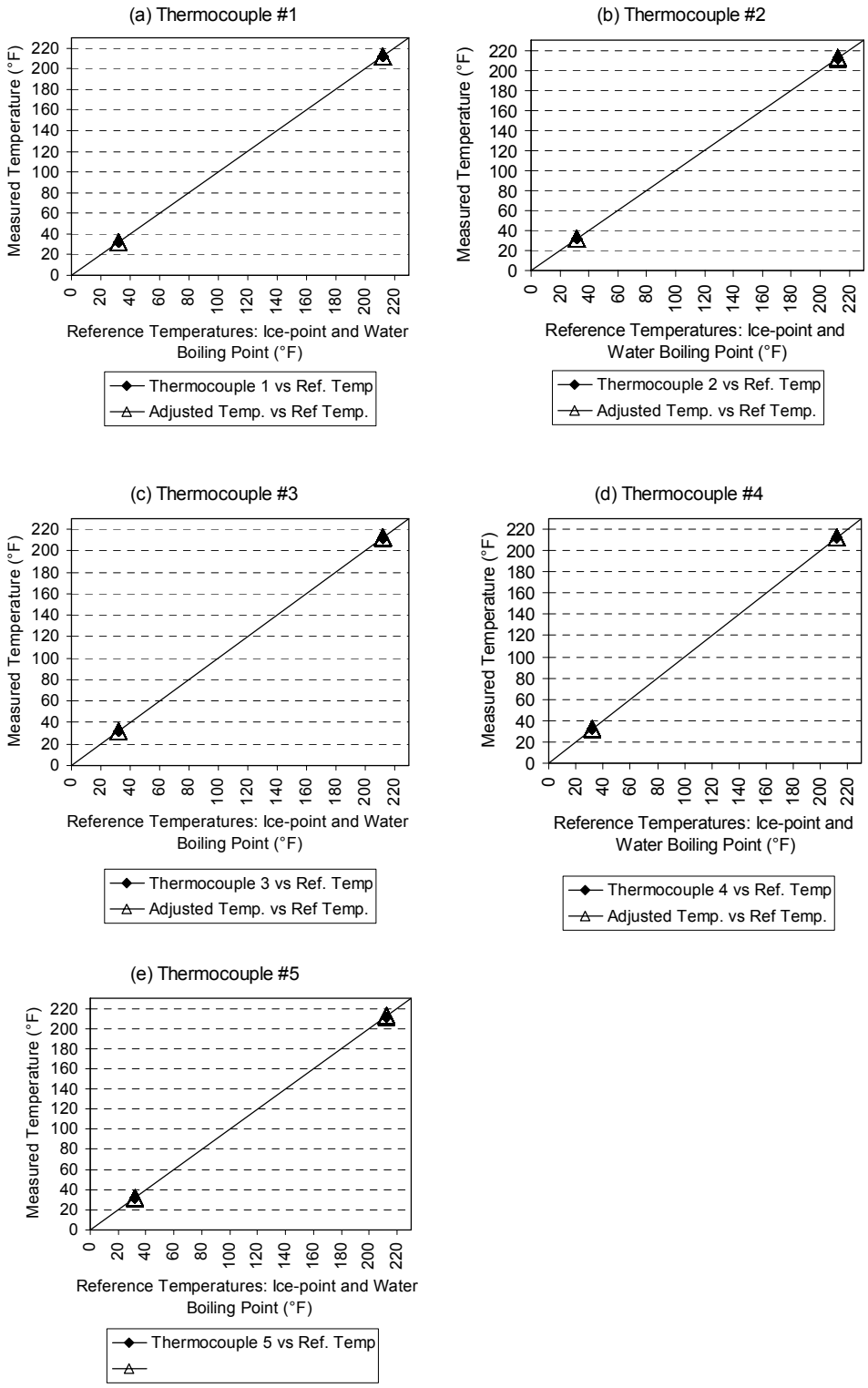


Figure C.5 *Temperature Calibrations of The Thermocouples.*

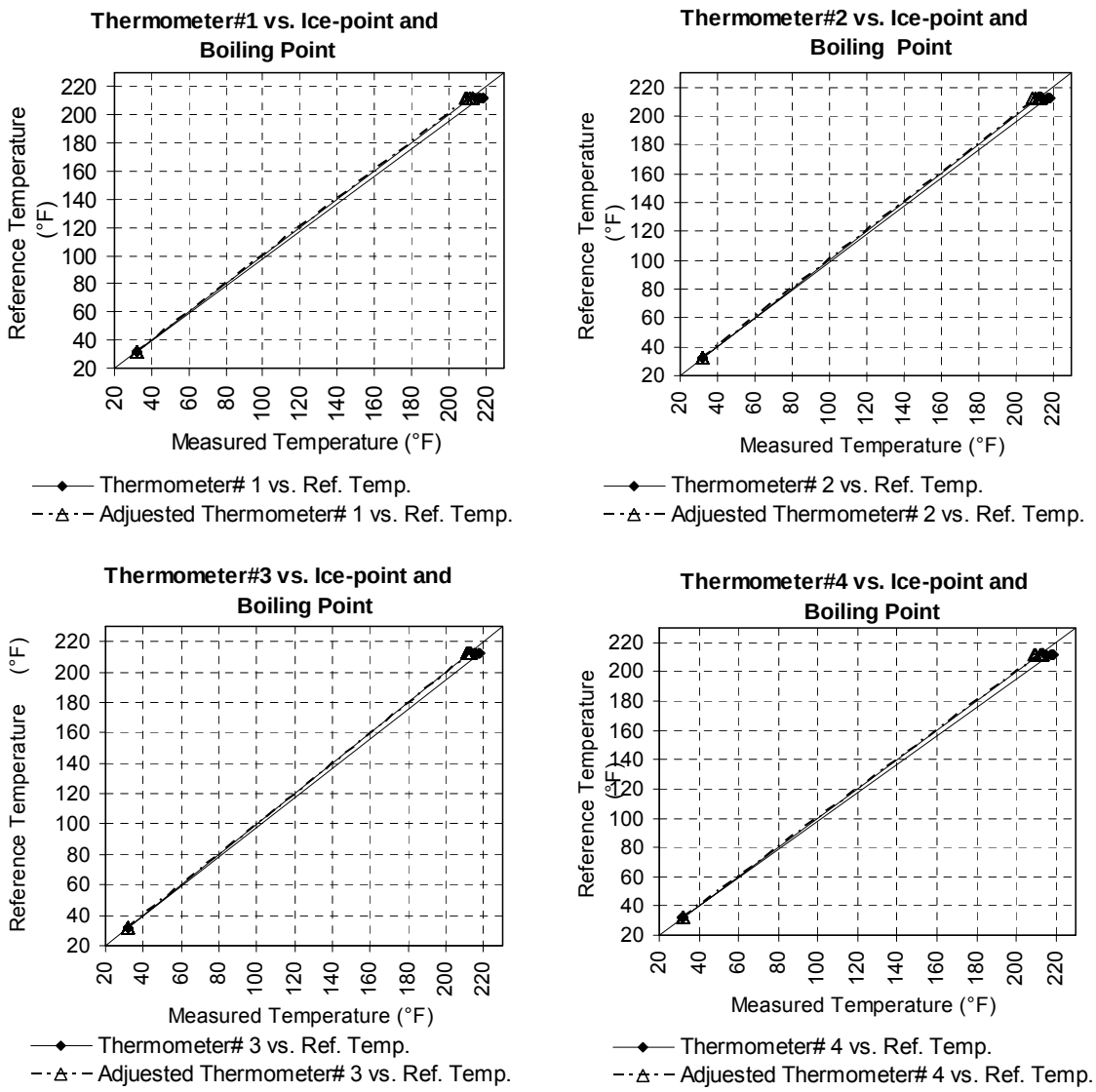


Figure C.6 *Temperature Calibrations of The Liquid-in-glass Thermometers.*

C.2.2 Instrument used for measuring solar radiation: pyranometer.

A photovoltaic-type sensor (LI-COR pyranometer) was used for my study. It was used to measure on-plain solar radiation on the Photovoltaic-Thermal panel. Calibration method that was used to calibrate the LI-COR Pyranometer is described by LI-COR, inc. (1991, p 15) as the following:

"The LI-COR SA Pyranometer has been calibrated against an Eppley Precision Spectral Pyranometer (PSP) of which the calibration is periodically confirmed. The calibration was performed under daylight conditions by a computer sampling of instantaneous readings from the Eppley and LI-COR pyranometers. Instantaneous readings were taken continuously for 10 minutes and then averaged. Sequential ten minute averaging periods were run from sunup to sundown for 3-4 days. These ten minute averages were then evaluated and used to compute an average calibration constant. The uncertainty of calibration is ±5%."

Klima (2000) calibrated photovoltaic-type sensors (LI-CORs) against PSP for his work at solar test bench at Langford Architecture building. He described that the PSP was reconditioned by the Eppley Laboratory and compared against a NIST standard pyranometer. Calibration constants were provided for the sensor by Eppley.

For my study, PSP at solar test bench was used to be a reference instrument for calibrating a LI-COR radiation sensor by the procedure that described by LI-COR. However, data logger at solar test bench was set to record data every 15 minute. Figure C.7 shows global solar radiation measured by PSP and LI-COR radiation sensor and Figure C.8 show solar radiation measured by PSP and calibrated LI-COR radiation sensor. Data from LI-COR (before and after calibration) is also plotted against PSP in Figure C.9 and C.10.

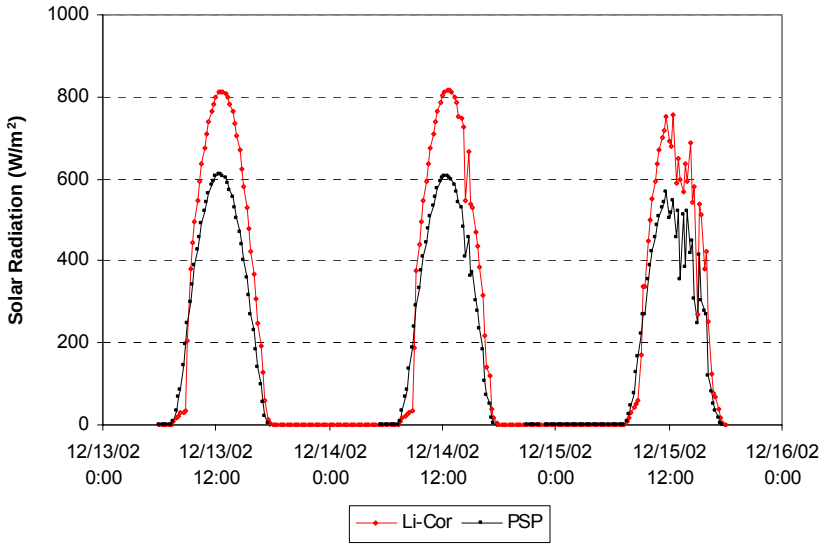


Figure C.7 *PSP and LI-COR.*

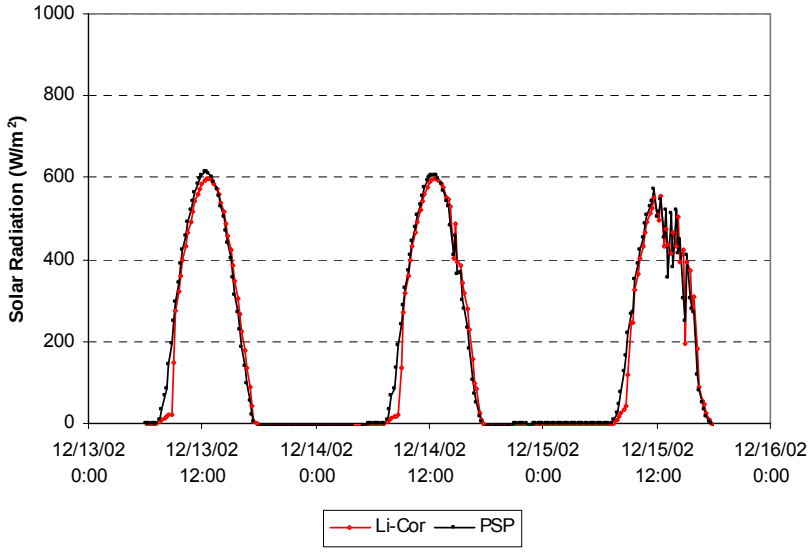


Figure C.8 *PSP and Calibrated LI-COR.*

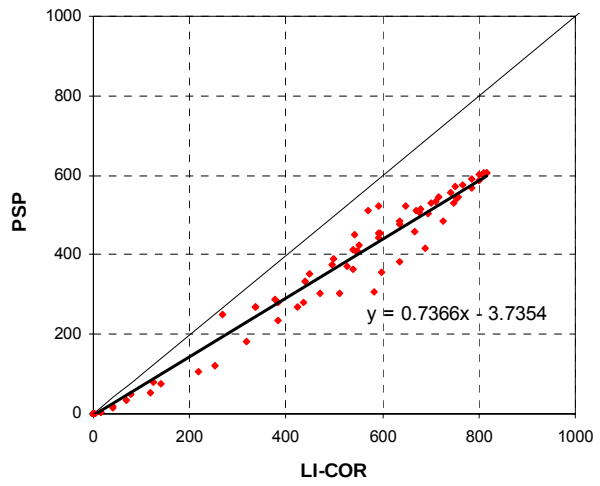


Figure C.9 *PSP Versus LI-COR*

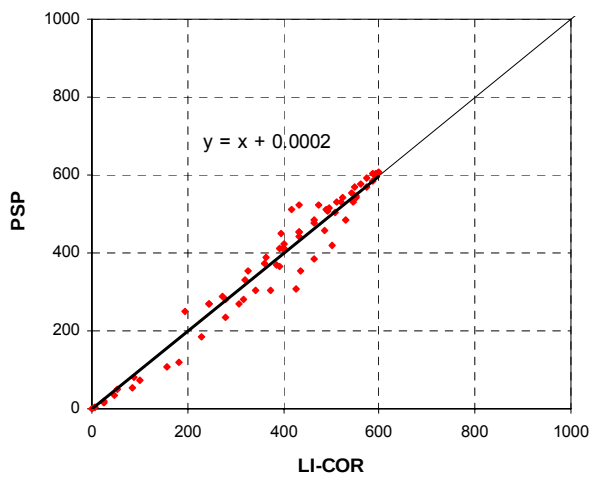


Figure C.10 *PSP Versus Calibrated LI-COR*

APPENDIX D

BUILDING ENERGY SIMULATION IN DOE-2

D.1 DOE-2 Input File of the Base-Case House

Figure D.1 shows the output from DrawBDL which represents the base-case house including surroundings. The DOE-2 input file of the base-case house is presented in the following pages.

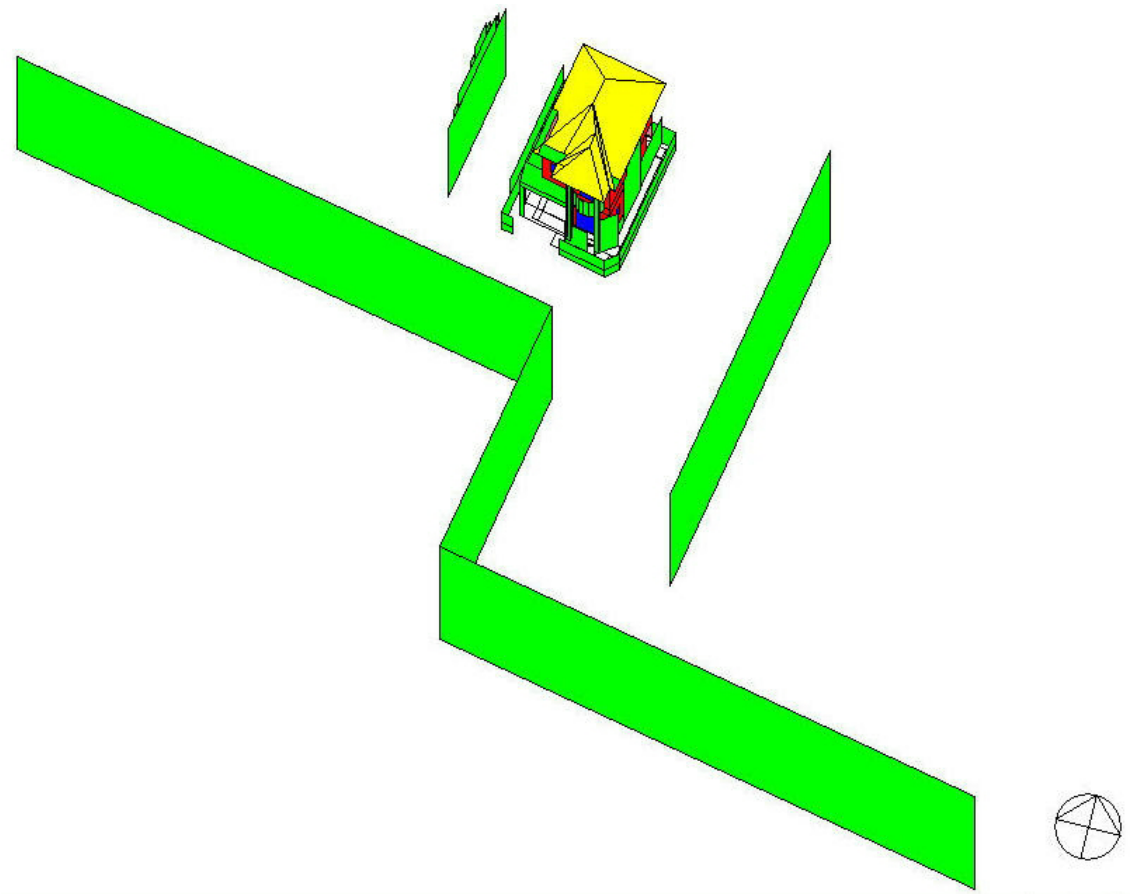


Figure D.1 *DrawBDL Output of the Base-Case House*

```
Copyright 2005 Sakkara Rasisuttha, Khon Kaen, Thailand

This program bears a copyright notice to prevent rights
from being claimed by any other party. This program shall
not be redistributed or sold without written approval from
the author.

$*************************  L  O  A  D  ***************************************

INPUT LOADS   ..

TITLE           LINE-1 *CASE STUDY HOUSE:THE JEERASAK'S HOUSE, THAILAND*
                      LINE-2 *Base-Case: Calibration #16*  ..

RUN-PERIOD      JAN 1 2000 THRU SEP 20 2000
                             SEP 25 2000 THRU DEC 31 2000  ..

ABORT           ERRORS  ..
DIAGNOSTIC      WARNINGS  ..

$----------------------------HOURLY REPORTS-------------------------------$
SCH-1    =SCHEDULE  THRU JAN 1 (ALL)(1,24)(1)
                    THRU DEC 31 (ALL)(1,24)(1) ..

G1  =  REPORT-BLOCK  VARIABLE-TYPE = GLOBAL
                     VARIABLE-LIST = (2,3,4,10,13,14,16,23,30)  ..

$ V-L (Global)= 2 = Ground temperature (Rankine)
$ V-L (Global)= 3 = Wet-bulb temperature (Fahrenheit)
$ V-L (Global)= 4 = Dry-bulb temperature (Fahrenheit)
$ V-L (Global)=10 = Humidity ratio (lb of water/lb of dry air)
$ V-L (Global)=16 = Cloud type in the DOE2 V.119 output,
$                   but definded as Wind speed (knots) in manual 2.1A
$ V-L (Global)=13 = Duffuse Solar in the DOE2 V.119 output,
$                   but definded as Total horizontal solar radiation
$                   from the weather file (But/hr-sq.ft).
$ V-L (Global)=14 = Total direct normal solar radiation
$                   from the weather file (But/hr-sq.ft).
$ V-L (Global)=23 = Heat loss by horizontal surface to sky (Btu/hr-sq.ft)
$ V-L (Global)=30 = Direct narmal extraterrestrial solar radiaton
$                   (But/hr-sq.ft).

H-REPORT-1 = H-R    R-SCH=SCH-1  R-B=(G1) ..

LOADS-REPORT    VERIFICATION =  (LV-A,LV-H)
                SUMMARY = (LS-A,LS-B,LS-C,LS-E,LS-K)  ..


                        $ BUILDING LACATION

$ CITY    = NONTHABURY (VICINITY OF BANGKOK)
$ COUNTRY = THAILAND

BUILDING-LOCATION
            LATITUDE   =   13.44
            LONGITUDE  =   -100.06
            ALTITUDE   =   6.627  $(2.02 m)
            TIME-ZONE  =   -7
            DAYLIGHT-SAVINGS  =  NO
           $CLEARNESS-NUMBER
            AZIMUTH    =   10.0
           $GROUND-T   =  (82,82,82,82,82,82,82,83.03,
           $              83.29,83.67,81.65,82.10)  Ground T. 2000 Pattarayut (2002)
           $GROUND-T   =  (80,80,82,82,80,80,80,
           $              80,80,80,78,74)   Ground T. 1999 Sreshthaputra (2003)
            GROUND-T   =  (81.3,81.5,84.7,84.6,84.4,82.4,
                           82.8,82.8,81.5,81.7,79.7,81.0)
            GROSS-AREA =  1315  .. $(122.00 m)


                        $ BUILDING DESCRIPTION

                 $ BUILDING CONSTRUCTIONS AND GLASS-TYPES

$ FLOOR=====================================================================
```

```
     $ FLOOR STRUCTURE
           $ CONCRETE SLAB
            $ THICKNESS:  3.937" (10 cm)
            $ REFERENCE: THERMAL PROPERTY FROM DOE-2 MATERIAL LIBRARY
            $ CODE-WORD: CC14 4" (10.16 cm) CONCRETE, HEAVY WEIGHT
            $ UNDRIE AGGREGATE, 140 lbs.
              $ THICKNESS     = 0.3333 Ft.
              $ CONDUCTIVITY  = 1.0417 Btu.Ft/Hr.Sq.Ft.*F
              $ DENSITY       = 140    Lb/cu.Ft.
              $ Specific Heat = 0.2    Btu/Lb.*F
              $ Resistance    = 0.32   Hr.Sq.Ft.*F/Btu

     $ FLOOR FINISHINGS
          $ CERAMIC TILE 8"x 8"
           $ THICKNESS: 0.3936" (1 cm)
           $ REFERENCE: ASHRAE(1997)
              $ THICKNESS     = 0.0328 Ft.
              $ CONDUCTIVITY  = 1.2709 Btu.Ft/Hr.Sq.Ft.*F  (2.2 W/m*K)
              $ DENSITY       = 16.25  Lb/cu.Ft.           (260 kg/m^3)
              $ Specific Heat = 0.1793 Btu/Lb.*F           (750 J/kg*K)
              $ Resistance    = ---    Hr.Sq.Ft.*F/Btu

          $ PARQUET
           $ THICKNESS: 3/4" (19.05 cm)
           $ REFERENCE: THERMAL PROPERTY FROM DOE-2 MATERIAL LIBRARY
           $ CODE-WORD: WD11 WOOD,HARD,3/4"
              $ THICKNESS     = 0.0625 Ft.
              $ CONDUCTIVITY  = 0.0916 Btu.Ft/Hr.Sq.Ft.*F  (k value) ( W/m*K)
              $ DENSITY       = 45.0   Lb/cu.Ft.           (kg/m^3)
              $ Specific Heat = 0.30   Btu/Lb.*F           (J/kg*K)
              $ Resistance    = 0.68   Hr.Sq.Ft.*F/Btu

MAT-FIC-1       =   MATERIAL  RESISTANCE = 2.437  ..  $ Resistance of fictitious layer

SOIL-12IN       =   MATERIAL
                     THICKNESS     = 1.0
                     CONDUCTIVITY  = 1.0
                     DENSITY       = 115
                     Specific-Heat = 0.1  ..
                   $ (Winkelmann 1998)

CERAMIC-MAT     =   MATERIAL
                     THICKNESS     = 0.0328
                     CONDUCTIVITY  = 1.2709
                     DENSITY       = 16.25
                     Specific-Heat = 0.1793  ..
                   $ Resistance    = ---


CERAMIC-LA = LAYERS MATERIAL=(MAT-FIC-1,SOIL-12IN,CC03)
                    INSIDE-FILM-RES = 0.92 ..

CERAMIC-FLOOR   =   CONSTRUCTION LAYERS =  CERAMIC-LA  ..

CERAMIC-LA-2 = LAYERS MATERIAL=(MAT-FIC-1,CC03)
                    INSIDE-FILM-RES = 0.92 ..

CERAMIC-FLOOR-2   =   CONSTRUCTION LAYERS =  CERAMIC-LA-2  ..


PARQUET-MAT     =   MATERIAL
                     THICKNESS     = 0.0625
                     CONDUCTIVITY  = 0.0916
                     DENSITY       = 45.0
                     Specific-Heat = 0.30
                     Resistance    = 0.68  ..

PARQUET-LA      =   LAYERS     MATERIAL =  (CC03, WD11)  ..

PARQUET-FLOOR   =   CONSTRUCTION LAYERS =  PARQUET-LA  ..

$ WALL=====================================================================
     $ WALL CONSTRUCTION
          $ BRICK
            $ THICKNESS:  3.937" (10 cm)
            $ REFERENCE: THERMAL PROPERTY FROM DOE-2 MATERIAL LIBRARY
            $ CODE-WORD: BK01 4" (10.16 cm) COMMON BRICK
```

```
              $ THICKNESS     = 0.3333 Ft.
              $ CONDUCTIVITY  = 0.4167 Btu.Ft/Hr.Sq.Ft.*F
              $ DENSITY       = 120    Lb/cu.Ft.
              $ Specific Heat = 0.2    Btu/Lb.*F
              $ Resistance    = 0.8    Hr.Sq.Ft.*F/Btu

     $ WALL FINISHINGS
          $ CEMENT
            $ THICKNESS: 0.3936" (1 cm)
            $ REFERENCE: CEMENT PLASTER, SAND AGGREGATE FROM
            $ STEIN&REYNOLDS (1992)
              $ THICKNESS     = 0.0328 Ft.
              $ CONDUCTIVITY  = 0.3079 Btu.Ft/Hr.Sq.Ft.*F  (0.533 W/m*K)
              $ DENSITY       = 116    Lb/cu.Ft.           (---kg/m^3)
              $ Specific Heat = 0.2    Btu/Lb.*F           (---J/kg*K)
              $ Resistance    = ---    Hr.Sq.Ft.*F/Btu

PLASTER-MAT   =   MATERIAL
                     THICKNESS     = 0.0328
                     CONDUCTIVITY  = 0.3079
                     DENSITY       = 116
                     Specific-Heat = 0.2  ..
                  $ Resistance    = ---

BRICK-LA      =   LAYERS     MATERIAL =  (PLASTER-MAT, BK01, PLASTER-MAT)  ..
BRICK-WALL    =   CONSTRUCTION LAYERS =  BRICK-LA  ..

$ CEILING=====================================================================
     $ CEILING CONSTRUCTION
          $ GYPSUM BOARD CEILING
            $ THICKNESS:  0.47" (12 cm)
            $ REFERENCE: THERMAL PROPERTY FROM DOE-2 MATERIAL LIBRARY
            $ CODE-WORD: GP01 1/2" (12.70 cm) GYPSUM OR PLASTER BOARD
              $ THICKNESS     = 0.0417 Ft.
              $ CONDUCTIVITY  = 0.0926 Btu.Ft/Hr.Sq.Ft.*F
              $ DENSITY       = 50     Lb/cu.Ft.
              $ Specific Heat = 0.2    Btu/Lb.*F
              $ Resistance    = 0.45   Hr.Sq.Ft.*F/Btu
          $ AIR GAP
            $ THICKNESS:  4" (10 cm)OR MORE
            $ REFERENCE: THERMAL PROPERTY FROM DOE-2 MATERIAL LIBRARY
            $ CODE-WORD: AL33 AIR LAYER, 4" OR MORE, HORIZONTAL ROOFS
              $ Resistance    = 0.92   Hr.Sq.Ft.*F/Btu
          $ FIBER GLASS INSULATION
            $ THICKNESS:  3.5"
            $ REFERENCE: THERMAL PROPERTY FROM DOE-2 MATERIAL LIBRARY
            $ CODE-WORD: IN02 MINERAL WOOL/FIBER R-11
              $ THICKNESS     = 0.2957 Ft.
              $ CONDUCTIVITY  = 0.0250 Btu.Ft/Hr.Sq.Ft.*F
              $ DENSITY       = 6      Lb/cu.Ft.
              $ Specific Heat = 0.2    Btu/Lb.*F
              $ Resistance    = 11.83  Hr.Sq.Ft.*F/Btu

GYPSUM-CEILING1   =  LAYERS
        MATERIAL   = (AL33, GP01)
        THICKNESS  = (1.0, 0.417)  ..
$ AIR GAP 30 CM
GYPSUM-CEILING-1ST  =  CONSTRUCTION LAYERS = GYPSUM-CEILING1  ..

GYPSUM-CEILING2   =  LAYERS
        MATERIAL   = (IN02, GP01)
        THICKNESS   = (0.2957, 0.0417)  ..
GYPSUM-CEILING-2ND  =  CONSTRUCTION LAYERS = GYPSUM-CEILING2  ..

$ ROOF========================================================================
     $ ROOFING MATERIAL
          $ CEMENT TILE(CPAC MONIA)
            $ THICKNESS:  1" (2.54 cm)
            $ REFERENCE: THERMAL PROPERTY FROM DOE-2 MATERIAL LIBRARY
            $ CODE-WORD: CM01 CEMENT 1" MORTAR
              $ THICKNESS     = 0.0833 Ft.
              $ CONDUCTIVITY  = 0.4167 Btu.Ft/Hr.Sq.Ft.*F
              $ DENSITY       = 116    Lb/cu.Ft.
              $ Specific Heat = 0.2    Btu/Lb.*F
              $ Resistance    = 0.2    Hr.Sq.Ft.*F/Btu
          $ ASBESTOS-CEMENT TILE
            $ THICKNESS:  0.25" (6.4 cm)
```

```
            $ REFERENCE: THERMAL PROPERTY FROM DOE-2 MATERIAL LIBRARY
            $ CODE-WORD: AB02
              $ THICKNESS     = 0.028  Ft.
              $ CONDUCTIVITY  = 0.3450 Btu.Ft/Hr.Sq.Ft.*F
              $ DENSITY       = 120    Lb/cu.Ft.
              $ Specific Heat = 0.2    Btu/Lb.*F
              $ Resistance    = 0.06    Hr.Sq.Ft.*F/Btu
          $ AIR GAP
            $ THICKNESS:  4" (10 cm)OR MORE
            $ REFERENCE: THERMAL PROPERTY FROM DOE-2 MATERIAL LIBRARY
            $ CODE-WORD: AL33 AIR LAYER, 4" OR MORE, HORIZONTAL ROOFS
              $ Resistance    = 0.92   Hr.Sq.Ft.*F/Btu

CEMENT-CPAC  =  MATERIAL
                THICKNESS     = 0.0833
                CONDUCTIVITY  = 0.4167
                DENSITY       = 116
                Specific-Heat = 0.2
                Resistance    = 0.2  ..

ROOF1  = LAYERS   MATERIAL = (CEMENT-CPAC,AL33)  ..

CEMENT-ROOF1  = CONSTRUCTION
                ABSORPTANCE = 0.88
                LAYERS = ROOF1  ..


$ WINDOW & DOOR ================================================================


GLASS-1  = GLASS-TYPE  GLASS-TYPE-CODE         = 1000   $ 3 mm CLEAR GLASS
                             FRAME-ABS         = 0.7
                             FRAME-CONDUCTANCE = 0.434  .. $

GLASS-2  = GLASS-TYPE  GLASS-TYPE-CODE         = 1000   $ 3 mm CLEAR GLASS
                             FRAME-ABS         = 0.7
                             FRAME-CONDUCTANCE = 0.434  ..


                        $ OCCUPANCY SCHEDULE

$ SPACE 1-1 : LIVING ROOM
OCC1-1WD   =   DAY-SCHEDULE
                (1,7) (0) (8) (0.25) (9,13) (0.25)
                (14,17)(0) (18) (0.25) (19)(0.75) (20,24)(0)  ..
OCC1-1WE   =   DAY-SCHEDULE
                (1,7) (0) (8) (0.25) (9,19) (0.35) (20,24)(0) ..
OCC1-1WEEK =   WEEK-SCHEDULE
                (WD) OCC1-1WD   (WEH) OCC1-1WE  ..
OCC1-1YEAR =   SCHEDULE
                THRU DEC 31 OCC1-1WEEK  ..



$ SPACE 1-2 : STAIRWAY
UNOCC1-2      =   DAY-SCHEDULE
                   (1,24) (0)  ..
UNOCC1-2WEEK  =   WEEK-SCHEDULE
                   DAYS  = (ALL)
                   DAY-SCHEDULE =  UNOCC1-2  ..
UNOCC1-2YEAR  =   SCHEDULE
                   THRU DEC 31   UNOCC1-2WEEK  ..

$ SPACE 1-3 : PLENUM
UNOCC1-3     =   DAY-SCHEDULE
                   (1,24) (0)  ..
UNOCC1-3WEEK  =   WEEK-SCHEDULE
                   DAYS  = (ALL)
                   DAY-SCHEDULE =  UNOCC1-3  ..
UNOCC1-3YEAR  =   SCHEDULE
                   THRU DEC 31   UNOCC1-3WEEK  ..

$ SPACE 1-6 : LAUNDAY AREA
UNOCC1-6      =   DAY-SCHEDULE
                   (1,24) (0)  ..
UNOCC1-6WEEK  =   WEEK-SCHEDULE
                   DAYS  = (ALL)
```

```
                    DAY-SCHEDULE =  UNOCC1-6  ..
UNOCC1-6YEAR  =   SCHEDULE
                    THRU DEC 31   UNOCC1-6WEEK  ..


$ SPACE 2-1 : MASTER BEDROOM
OCC2-1WD   =   DAY-SCHEDULE
                (1,7) (0.75) (8,19) (0) (20,24) (0.75)  ..
OCC2-1WE   =   DAY-SCHEDULE
                (1,7) (0.75) (8,19) (0) (20,24) (0.75)  ..
OCC2-1WEEK =   WEEK-SCHEDULE
                (WD) OCC2-1WD   (WEH) OCC2-1WE  ..
OCC2-1YEAR =   SCHEDULE
                THRU DEC 31 OCC2-1WEEK  ..

$ SPACE 2-2 : BEDROOM 2
OCC2-2WD   =   DAY-SCHEDULE
                (1,24) (0)  ..
OCC2-2WE   =   DAY-SCHEDULE
                (1,7) (0.25) (8,19) (0) (20,24) (0.25)  ..
OCC2-2WEEK =   WEEK-SCHEDULE
                (WD) OCC2-2WD   (WEH) OCC2-2WE  ..
OCC2-2YEAR =   SCHEDULE
                THRU DEC 31 OCC2-2WEEK  ..

$ SPACE 2-3 : BEDROOM 3 (NOT USED AS A BEDROOM, BUT FOR VERSATILE USES)
OCC2-3WD   =   DAY-SCHEDULE
                (1,24) (0)  ..
OCC2-3WE   =   DAY-SCHEDULE
                (1,24) (0)  ..
OCC2-3WEEK =   WEEK-SCHEDULE
                (WD) OCC2-3WD   (WEH) OCC2-3WE  ..
OCC2-3YEAR =   SCHEDULE
                THRU DEC 31 OCC2-3WEEK  ..

$ SPACE 2-4 : BATHROOM & 2ND FLOOR HALL
UNOCC2-4      =   DAY-SCHEDULE
                  (1,24) (0)  ..
UNOCC2-4WEEK =   WEEK-SCHEDULE
                    DAYS  = (ALL)
                    DAY-SCHEDULE =  UNOCC2-4  ..
UNOCC2-4YEAR  =   SCHEDULE
                    THRU DEC 31   UNOCC2-4WEEK  ..


                         $ LIGHTING SCHEDULE

$ SPACE 1-1 : LIVING RM (32 W), DINING RM (32 W)
$             KITCHEN (32 W), BATHROOM (3.2 W)
$ LIGHT IN BATHROOM IS USED FOR SHORT PERIODS OF TIME
$ AND ITS LIGHT SCHEDULE IS IN THE SAME PROFILE AS LIVING RM,
$ DINING RM AND KITCHEN, SO THE POWER (WATT) OF LIGHT IS
$ DEFINED ABOUT 1/10 OF IT ACTUAL VALUE (3.2 W).


LIGHT1-1WD   =  DAY-SCHEDULE
                (1,8)(0) (9,13)(0)
                (14,17)(0) (18,20)(1) (21,22)(0.75)
                (23)(0) (24)(0)  ..
LIGHT1-1WE   =  DAY-SCHEDULE
                (1,8)(0) (9,13)(0)
                (14,17)(0) (18,20)(1) (21,22)(0.75)
                (23)(0) (24)(0)  ..
LIGHT1-1WEEK =  WEEK-SCHEDULE
                (WD) LIGHT1-1WD   (WEH) LIGHT1-1WE  ..
LIGHT1-1YEAR =  SCHEDULE
                 THRU DEC 31 LIGHT1-1WEEK  ..


$ SPACE 1-2 : STAIRWAY (32 W)
LIGHT1-2WD   =  DAY-SCHEDULE
                (1,8)(0) (9,13)(0) (14,17)(0) (18)(0)
                (19,20)(1) (21)(0.5) (22,24)(0)  ..
LIGHT1-2WE   =  DAY-SCHEDULE
                (1,8)(0) (9,13)(0) (14,17)(0) (18)(0)
                (19,20)(1) (21)(0.5) (22,24)(0)  ..
LIGHT1-2WEEK =  WEEK-SCHEDULE
```

```
                (WD) LIGHT1-2WD   (WEH) LIGHT1-2WE  ..
LIGHT1-2YEAR =  SCHEDULE
                 THRU DEC 31 LIGHT1-2WEEK  ..

$ SPACE 1-6 : LAUNDRY AREA (32 W)
LIGHT1-6WD   =  DAY-SCHEDULE
                (1,8)(0) (9,13)(0)
                (14,17)(0) (18,20)(0) (21,24)(0)  ..
LIGHT1-6WE   =  DAY-SCHEDULE
                (1,8)(0) (9,13)(0)
                (14,17)(0) (18,21)(0) (22,24)(0)  ..
LIGHT1-6WEEK =  WEEK-SCHEDULE
                (WD) LIGHT1-6WD   (WEH) LIGHT1-6WE  ..
LIGHT1-6YEAR =  SCHEDULE
                 THRU DEC 31 LIGHT1-6WEEK  ..


$ SPACE 2-1 : MASTER BEDROOM (2 X 32 W = 64 W)
LIGHT2-1WD   =   DAY-SCHEDULE
                (1,7)(0) (8,19)(0) (20)(0.33)
                (21,22)(1)  (23)(0.5) (24)(0)  ..
LIGHT2-1WE   =   DAY-SCHEDULE
                (1,7)(0) (8,19)(0) (20)(0.33)
                (21,22)(1)  (23)(0.5) (24)(0)  ..
LIGHT2-1WEEK =   WEEK-SCHEDULE
                (WD) LIGHT2-1WD   (WEH) LIGHT2-1WE  ..
LIGHT2-1YEAR =   SCHEDULE
                THRU DEC 31 LIGHT2-1WEEK  ..

$ SPACE 2-2 : BEDROOM 2 (32 W)
LIGHT2-2WD   =  DAY-SCHEDULE
                 (1,24)(0)  .. $ Bedroom 2 is not occupied in the weekday.
LIGHT2-2WE   =  DAY-SCHEDULE
                 (1,7)(0) (8,18)(0) (19,21)(0) (22,24)(1)  ..
LIGHT2-2WEEK =  WEEK-SCHEDULE
                 (WD) LIGHT2-2WD   (WEH) LIGHT2-2WE  ..
LIGHT2-2YEAR =  SCHEDULE
                 THRU DEC 31 LIGHT2-2WEEK  ..

$ SPACE 2-3 : BEDROOM 3 (32 W)
LIGHT2-3WD   =  DAY-SCHEDULE
                (1,19)(0) (20)(0.16) (21,24)(0)  ..
LIGHT2-3WE   =  DAY-SCHEDULE
                (1,19)(0) (20)(0.16) (21,24)(0)  ..
LIGHT2-3WEEK =  WEEK-SCHEDULE
                (WD) LIGHT2-3WD   (WEH) LIGHT2-3WE  ..
LIGHT2-3YEAR =  SCHEDULE
                 THRU DEC 31 LIGHT2-3WEEK  ..

$ SPACE 2-4 : BATHROOM(32 W) & 2ND FLOOR HALL (32 W)
LIGHT2-4WD   =   DAY-SCHEDULE
                 (1,6)(0)  (7)(0.33)  (8,18)(0)  (19)(0.33)  (20,24)(0)  ..
LIGHT2-4WE   =   DAY-SCHEDULE
                 (1,7)(0)  (8)(0.33)  (9,18)(0)  (19)(0.33)  (20,24)(0)  ..
LIGHT2-4WEEK =   WEEK-SCHEDULE
                 (WD)LIGHT2-4WD   (WEH) LIGHT2-4WE  ..
LIGHT2-4YEAR =   SCHEDULE
                  THRU DEC 31 LIGHT2-4WEEK  ..


                         $ EQUIPMENT SCHEDULE

$ SPACE 1-1 : LIVING ROOM (TV-85 W + Electric Fan-60 W = 145 W)
$ DINING ROOM (MICROWAVE OVEN-1000 W + TOASTER-700 W = 1700 W)
$ KITCHEN ROOM (REFRIGERATOR-150 W (657 kwh/year) + ELECTRIC RICE COOKER-700 W = 650 W)
$
$ TOTAL  = 2495 W OR 2.495 KW (Adjusted to 2.3 KW)

EQUIP1-1WD   =   DAY-SCHEDULE
                (1,7)(0.0326)  (8)(0.0519)  (9,17)(0.0326)  (18)(0.109)
                (19,20)(0.0736)  (21,24)(0.0326)  ..
EQUIP1-1WE   =   DAY-SCHEDULE
                (1,7)(0.0326)  (8)(0.0519)  (9,10)(0.0326)
                (11,17)(0.0736)  (18)(0.109) (19,20)(0.0736)
                (21,24)(0.0326)  ..
EQUIP1-1WEEK =   WEEK-SCHEDULE
```

```
                (WD) EQUIP1-1WD   (WEH) EQUIP1-1WE  ..
EQUIP1-1YEAR =   SCHEDULE
                THRU DEC 31 EQUIP1-1WEEK  ..


$ SPACE 1-6 SEMI-OUTDOOR: LUANDRY AREA (CLOTH WASHER = 260 W)

EQUIP1-6WD   =  DAY-SCHEDULE
                 (1,8)(0) (9)(0.25)  (10,24)(0)  ..
EQUIP1-6WE   =  DAY-SCHEDULE
                 (1,8)(0) (9)(0.25)  (10,24)(0)  ..
EQUIP1-6WEEK =  WEEK-SCHEDULE
                 (WD) EQUIP1-6WD   (WEH) EQUIP1-6WE  ..
EQUIP1-6YEAR =  SCHEDULE
                 THRU DEC 31 EQUIP1-6WEEK  ..



$ SPACE 2-1 : MASTER BEDROOM (TV-95 W + ELEC. FAN 60 W + DESK LAMP 60 W = 215 W)
EQUIP2-1WD   =   DAY-SCHEDULE
                (1,7)(0) (8,20)(0) (21)(0.44) (22)(0.22) (23)(0.22)  (24)(0) ..
EQUIP2-1WE   =   DAY-SCHEDULE
                (1,7)(0) (8,20)(0) (21)(0.44) (22)(0.44) (23)(0.22)  (24)(0) ..
EQUIP2-1WEEK =   WEEK-SCHEDULE
                 (WD)EQUIP2-1WD   (WEH) EQUIP2-1WE  ..
EQUIP2-1YEAR =   SCHEDULE
                  THRU DEC 31 EQUIP2-1WEEK  ..


$ SPACE 2-2 : BEDROOM 2 (TV-48 W + DESK LAMP-60 W = 108 W)
EQUIP2-2WD   =   DAY-SCHEDULE
                 (1,24)(0)  ..
EQUIP2-2WE   =   DAY-SCHEDULE
                 (1,7)(0) (8,20)(0) (21)(0) (22)(0) (23)(0.44)  (24)(0)  ..
EQUIP2-2WEEK =   WEEK-SCHEDULE
                 (WD)EQUIP2-2WD   (WEH) EQUIP2-2WE  ..
EQUIP2-2YEAR =   SCHEDULE
                  THRU DEC 31 EQUIP2-2WEEK  ..

$ SPACE 2-3 : BEDROOM 3 (IRON = 1200 W)
EQUIP2-3WD   =   DAY-SCHEDULE
                 (1,15)(0)  (16)(0.25)  (17,24) (0)  ..
EQUIP2-3WE   =   DAY-SCHEDULE
                 (1,15)(0)  (16)(0.25)  (17,24) (0)  ..
EQUIP2-3WEEK =   WEEK-SCHEDULE
                 (WD)EQUIP2-3WD   (WEH) EQUIP2-3WE  ..
EQUIP2-3YEAR =   SCHEDULE
                  THRU DEC 31 EQUIP2-3WEEK  ..

$ SPACE 2-4 : BATHROOM & HALL
$             (REFRIGERATOR 100 W)
EQUIP2-4WD   =   DAY-SCHEDULE
                 (1,24)(0.486)  ..
EQUIP2-4WE   =   DAY-SCHEDULE
                 (1,24)(0.486)  ..
EQUIP2-4WEEK =   WEEK-SCHEDULE
                 (WD)EQUIP2-4WD   (WEH) EQUIP2-4WE  ..
EQUIP2-4YEAR =   SCHEDULE
                  THRU DEC 31 EQUIP2-4WEEK  ..

$ WASHING MACHINE

WASHING-WD   =   DAY-SCHEDULE
                (1,8) (0) (9) (0.3) (10,24) (0)  ..
WASHING-WE   =   DAY-SCHEDULE
                (1,8) (0) (9) (0.5) (10,24) (0)  ..
WASHING-WEEK =   WEEK-SCHEDULE
                (WD) WASHING-WD   (WEH) WASHING-WE  ..
WASHING-YEAR =   SCHEDULE
                THRU DEC 31 WASHING-WEEK  ..

                         $ INFILTRATION SCHEDULE

INFIL-DAY   =  DAY-SCHEDULE
                (1,24) (1)  ..
INFIL-WEEK  =  WEEK-SCHEDULE
                DAYS = (ALL)
```

```
                DAY-SCHEDULE = INFIL-DAY  ..
INFIL-YEAR  =  SCHEDULE
                THRU DEC 31 INFIL-WEEK  ..

INFIL-DAY-L   =  DAY-SCHEDULE
                (1,7) (0.1) (8,18) (1) (19,24) (0.1)  ..
INFIL-WEEK-L  =  WEEK-SCHEDULE
                DAYS = (ALL)
                DAY-SCHEDULE = INFIL-DAY-L  ..
INFIL-YEAR-L  =  SCHEDULE
                THRU DEC 31 INFIL-WEEK-L  ..

$ ATTIC'S INFILTRATION SCHEDULE

INFIL-DAY-ATT   =  DAY-SCHEDULE
                (1,7) (1) (8,20) (0.2) (21,24) (1) ..
INFIL-WEEK-ATT  =  WEEK-SCHEDULE
                DAYS = (ALL)
                DAY-SCHEDULE = INFIL-DAY-ATT  ..
INFIL-YEAR-ATT  =  SCHEDULE
                THRU DEC 31 INFIL-WEEK-ATT  ..

                        $  SHADING SCHEDULE

CURTAIN-1-DAY   =  DAY-SCHEDULE
                (1,24) (0.8)  ..
CURTAIN-1-WEEK  =  WEEK-SCHEDULE
                DAYS = (ALL)
                DAY-SCHEDULE = CURTAIN-1-DAY  ..
CURTAIN-1   =  SCHEDULE
                THRU DEC 31 CURTAIN-1-WEEK  ..


CURTAIN-2-DAY   =  DAY-SCHEDULE
                (1,24) (0.5)  ..
CURTAIN-2-WEEK  =  WEEK-SCHEDULE
                DAYS = (ALL)
                DAY-SCHEDULE = CURTAIN-2-DAY  ..
CURTAIN-2   =  SCHEDULE
                THRU DEC 31 CURTAIN-2-WEEK  ..


                        $ SET DEFAULT VALUES

$SET-DEFAULT FOR SPACE FLOOR-WEIGHT=0  ..

$SET-DEFAULT FOR WINDOW HEIGHT=4.0 GLASS-TYPE=W-1  Y=3  ..

                          $ GENERAL SPACE CONDITIONS

LIVING-SPACE   =  SPACE-CONDITIONS
                   TEMPERATURE        =  (85) $ AVERAGE MEASURED TEMPERATURE OF LIVING RM.
                  $PEOPLE-SCHEDULE    =  INDIVIDUAL
                   NUMBER-OF-PEOPLE   =  3.3            $ 3 ADOUTS AND ONE YEAR OLD BABY
                   PEOPLE-HEAT-GAIN   =  400
                  $LIGHTING-SCHEDULE  =  INDIVIDUAL
                   LIGHTING-TYPE      =  SUS-FLUOR
                   LIGHT-TO-SPACE     =  0.8
                  $EQUIP-SCHEDULE     =  INDIVIDUAL
                  $EQUIPMENT-KW       =  INDIVIDUAL
                   INF-METHOD         =  AIR-CHANGE
                   AIR-CHANGES/HR     =  1            $ INDIVIDUAL
                   INF-SCHEDULE       =  INFIL-YEAR
                   ZONE-TYPE          =  UNCONDITIONED  $ INDIVIDUAL
                   FURNITURE-TYPE     =  HEAVY
                   FLOOR-WEIGHT       =  0  ..
       $  Set FLOOR-WEIGHT = 0 for automatic calculation of Custom Weighting Factor (CWF)
$PLENUM-SPACE


PLENUM-SPACE =  SPACE-CONDITIONS
                  ZONE-TYPE          =  PLENUM  ..



ATTIC-SPACE    =  SPACE-CONDITIONS
                   TEMPERATURE        =  (87.5) $ AVERAGE MEASURED TEMPERATURE OF ATTIC
```

```
                  INF-METHOD         =  AIR-CHANGE
                  AIR-CHANGES/HR     =  5             $ INDIVIDUAL
                  INF-SCHEDULE       =  INFIL-YEAR-ATT
                  ZONE-TYPE          =  CONDITIONED    $ INDIVIDUAL
                  FLOOR-WEIGHT       =  0  ..

ATTIC-SPACE-B  =  SPACE-CONDITIONS    $  THERMAL MASS IN THE ROOF (CONCRETE BEAMS AND BRICK WALLS)
                  TEMPERATURE        =  (87.5) $ AVERAGE MEASURED TEMPERATURE OF ATTIC
                  INF-METHOD         =  AIR-CHANGE
                  AIR-CHANGES/HR     =  0             $ INDIVIDUAL
                  INF-SCHEDULE       =  INFIL-YEAR-ATT
                  ZONE-TYPE          =  CONDITIONED    $ INDIVIDUAL
                  FLOOR-WEIGHT       =  0  ..

                        $ SPECIFIC SPACE DETAILS

$ SPACE 1-1 : LIVING ROOM, DINING AREA, KITCHEN, BATHROOM
SPACE1-1   =   SPACE
               SPACE-CONDITIONS  =  LIVING-SPACE
               PEOPLE-SCHEDULE   =  OCC1-1YEAR
               LIGHTING-SCHEDULE =  LIGHT1-1YEAR
               EQUIP-SCHEDULE    =  EQUIP1-1YEAR
               LIGHTING-KW       =  0.0992
               EQUIPMENT-KW      =  2.3      $ was 2.495
               INF-SCHEDULE      =  INFIL-YEAR-L
               INF-METHOD        =  AIR-CHANGE
               AIR-CHANGES/HR    =  10            $ INDIVIDUAL
               AREA              =  757.44   $ 60% larger than the actual (473.40)
               VOLUME            =  2329.7  .. $ 60% less than tha actual (3882.87)

RIGHT1-1   =   EXTERIOR-WALL
                 WIDTH   = 12.139
                 HEIGHT  = 8.202
                 AZIMUTH = 90
                 X = 32.82     Y = 10.59
                 Z = 0
                 CONSTRUCTION = BRICK-WALL  ..

WINDOW-R-1-1 =  WINDOW
                 WIDTH   = 2.293
                 HEIGHT  = 2.949
                 X = 4.593
                 Y = 2.953
                 GLASS-TYPE = GLASS-1
                 SHADING-SCHEDULE = CURTAIN-1 $ ACCOUNTED FOR THE CURTAIN
                 FRAME-WIDTH = 0.33  ..

BACK1-7   =   EXTERIOR-WALL
                 WIDTH   = 1.969
                 HEIGHT  = 8.202
                 AZIMUTH = 0
                 X = 32.82    Y = 22.729
                 Z = 0
                 CONSTRUCTION = BRICK-WALL  ..

RIGHT1-2   =   EXTERIOR-WALL
                 WIDTH   = 6.562
                 HEIGHT  = 8.202
                 AZIMUTH = 90
                 X = 30.851
                 Y = 22.729
                 Z = 0
                 CONSTRUCTION = BRICK-WALL  ..

WINDOW-R-1-2 =  WINDOW
                 WIDTH   = 2.293
                 HEIGHT  = 2.949
                 X = 1.8045
                 Y = 2.953
                 GLASS-TYPE = GLASS-1
                 SHADING-SCHEDULE = CURTAIN-1 $ ACCOUNTED FOR THE CURTAIN
                 FRAME-WIDTH = 0.33  ..


RIGHT1-4   =   EXTERIOR-WALL
                 WIDTH   = 12.139
                 HEIGHT  = 8.202
```

```
                AZIMUTH = 90
                X = 30.851
                Y = 29.291
                Z = 0
                CONSTRUCTION = BRICK-WALL  ..

WINDOW-R-1-4 =  WINDOW
                WIDTH   = 5.246
                HEIGHT  = 5.902
                X = 3.1165
                Y = 0
                GLASS-TYPE = GLASS-1
                SHADING-SCHEDULE = CURTAIN-1 $ ACCOUNTED FOR THE CURTAIN
                FRAME-WIDTH = 0.33  ..


BACK1-2   =   EXTERIOR-WALL
                WIDTH   = 10.499
                HEIGHT  = 8.202
                AZIMUTH = 0
                X = 30.851    Y = 41.43
                Z = 0
                CONSTRUCTION = BRICK-WALL  ..

WINDOW-B-1-2 =  WINDOW
                WIDTH   = 5.246
                HEIGHT  = 2.949
                X = 2.6245
                Y = 2.953
                GLASS-TYPE = GLASS-1
                FRAME-WIDTH = 0.33  ..


BACK1-1   =   EXTERIOR-WALL
                WIDTH   = 9.842
                HEIGHT  = 8.202
                AZIMUTH = 0
                X = 20.351    Y = 41.43
                Z = 0
                CONSTRUCTION = BRICK-WALL  ..

WINDOW-B-1-1-1 = WINDOW    $ DOOR WITH GLASS
                 WIDTH   = 2.129
                 HEIGHT  = 3.232
                 X = 0.82
                 Y = 0
                GLASS-TYPE = GLASS-1
                FRAME-WIDTH = 1  ..


WINDOW-B-1-1-2 = WINDOW
                 WIDTH   = 3.933
                 HEIGHT  = 2.949
                 X = 3.609
                 Y = 2.953
                GLASS-TYPE = GLASS-1
                FRAME-WIDTH = 0.33  ..

LEFT1-3    =   EXTERIOR-WALL
                WIDTH   = 11.574
                HEIGHT  = 8.202
                AZIMUTH = 270
                X = 10.51
                Y = 41.43
                Z = 0
                CONSTRUCTION = BRICK-WALL  ..

WINDOW-L-1-3 = WINDOW
               WIDTH   = 3.933
               HEIGHT  = 2.949
               X = 1.2155
               Y = 2.953
                GLASS-TYPE = GLASS-1
                FRAME-WIDTH = 0.33  ..


LEFT1-4    =   EXTERIOR-WALL
```

```
                 WIDTH   = 4.55
                 HEIGHT  = 8.202
                 AZIMUTH = 270
                 X = 10.51
                 Y = 34.406
                 Z = 0
                 CONSTRUCTION = BRICK-WALL  ..

WINDOW-L-1-4 = WINDOW
                WIDTH   = 2.951
                HEIGHT  = 1.0
                X = 0.6345
                Y = 5.232
                 GLASS-TYPE = GLASS-1
                 SHADING-SCHEDULE = CURTAIN-1 $ SANDED GLASS
                 FRAME-WIDTH = 0.33  ..


LEFT1-1    =   EXTERIOR-WALL
                 WIDTH   = 11.483
                 HEIGHT  = 8.202
                 AZIMUTH = 270
                 X = 19.696
                 Y = 22.073
                 Z = 0
                 CONSTRUCTION = BRICK-WALL  ..

WINDOW-L-1-1 =  WINDOW
                 WIDTH   = 3.933
                 HEIGHT  = 2.949
                 X = 3.117
                 Y = 2.953
                 GLASS-TYPE = GLASS-1
                 FRAME-WIDTH = 0.33  ..


FRONT1-1   =   EXTERIOR-WALL
                 WIDTH   = 13.124
                 HEIGHT  = 8.202
                 AZIMUTH = 180
                 X = 19.696
                 Y = 10.59
                 Z = 0
                 CONSTRUCTION = BRICK-WALL  ..

WINDOW-F-1-1 =  WINDOW
                 WIDTH   = 7.867
                 HEIGHT  = 5.902
                 X = 0.984
                 Y = 0
                 GLASS-TYPE = GLASS-1
                 SHADING-SCHEDULE = CURTAIN-1 $ ACCOUNTED FOR THE CURTAIN
                 FRAME-WIDTH = 0.33 ..

INTER1-2   =   INTERIOR-WALL
                 AREA = 37.319
                 NEXT-TO = SPACE1-1
                 CONSTRUCTION = BRICK-WALL  ..

INTER1-3   =   INTERIOR-WALL
                 AREA = 78.03
                 NEXT-TO = SPACE1-1
                 CONSTRUCTION = BRICK-WALL  ..

FLOOR1-1   =  UNDERGROUND-FLOOR
                 HEIGHT = 47.34
                 WIDTH = 100
                 TILT = 180
                 U-EFFECTIVE = 0.03
                 CONSTRUCTION = CERAMIC-FLOOR  ..

CEILING1-1-A =  INTERIOR-WALL
                 AREA = 151.35
                 NEXT-TO = SPACE1-3
                 TILT = 0
                 CONSTRUCTION = GYPSUM-CEILING-1ST  ..
```

```
CEILING1-1-B =  INTERIOR-WALL
                 AREA = 68.89
                 NEXT-TO = SPACE1-3
                 TILT = 0
                 CONSTRUCTION = GYPSUM-CEILING-1ST  ..

CEILING1-1-C =  INTERIOR-WALL
                 AREA = 120.56
                 NEXT-TO = SPACE1-3
                 TILT = 0
                 CONSTRUCTION = GYPSUM-CEILING-1ST  ..

CEILING1-1-D =  INTERIOR-WALL
                 AREA = 63.23
                 NEXT-TO = SPACE1-3
                 TILT = 0
                 CONSTRUCTION = GYPSUM-CEILING-1ST  ..

CEILING1-1-E =  INTERIOR-WALL
                 AREA = 42.49
                 NEXT-TO = SPACE1-3
                 TILT = 0
                 CONSTRUCTION = GYPSUM-CEILING-1ST  ..


$ SPACE 1-2 :  STAIRWAY   (CORE)
  SPACE1-2   =   SPACE
                SPACE-CONDITIONS  =  LIVING-SPACE
                PEOPLE-SCHEDULE   =  UNOCC1-2YEAR
                LIGHTING-SCHEDULE =  LIGHT1-2YEAR
                LIGHTING-KW       =  0.032
                EQUIPMENT-KW      =  0.0
                AREA              =  98.17
                VOLUME            =  1835.79  ..

BACK1-4    =   EXTERIOR-WALL
                 WIDTH   = 3.281
                 HEIGHT  = 10.499
                 AZIMUTH = 0
                 X = 10.51
                 Y = 29.947
                 Z = 0
                 CONSTRUCTION = BRICK-WALL  ..

BACK2-3    =   EXTERIOR-WALL
                 WIDTH   = 1.969
                 HEIGHT  = 8.202
                 AZIMUTH = 0
                 X = 9.198
                 Y = 29.947
                 Z = 10.499
                 CONSTRUCTION = BRICK-WALL  ..

LEFT1-2    =   EXTERIOR-WALL
                 WIDTH   = 7.874
                 HEIGHT  = 18.701
                 AZIMUTH = 270
                 X = 7.229
                 Y = 29.947
                 Z = 0
                 CONSTRUCTION = BRICK-WALL  ..

WINDOW-L-1-2 = WINDOW
                WIDTH   = 3.277
                HEIGHT  = 5.902
                X = 1.9685
                Y = 10.499
                 GLASS-TYPE = GLASS-2
                 SHADING-SCHEDULE = CURTAIN-2 $ ACCOUNTED FOR THE CURTAIN
                 FRAME-WIDTH = 0.33  ..


FRONT1-2    =   EXTERIOR-WALL
                 WIDTH   = 12.467
                 HEIGHT  = 10.499
                 AZIMUTH = 180
                 X = 7.229
```

```
                Y = 22.073
                Z = 0
                CONSTRUCTION = BRICK-WALL  ..

WINDOW-F-1-2 = WINDOW    $ FRONT DOOR (STEEL FRAME DOOR WITH GLASS)
               WIDTH   = 1.95
               HEIGHT  = 5.297
               X = 8.858
               Y = 0
                GLASS-TYPE = GLASS-1
                SHADING-SCHEDULE = CURTAIN-2 $ ACCOUNTED FOR THE CURTAIN
                FRAME-WIDTH = 0.33  ..


FRONT2-2    =   EXTERIOR-WALL
                WIDTH   = 1.969
                HEIGHT  = 8.202
                AZIMUTH = 180
                X = 7.229
                Y = 22.073
                Z = 10.499
                CONSTRUCTION = BRICK-WALL  ..

INTER1-1   =   INTERIOR-WALL
                AREA = 78.034
                NEXT-TO = SPACE1-1
                CONSTRUCTION = BRICK-WALL  ..

FLOOR1-5  =  UNDERGROUND-FLOOR
                AREA = 89.99
                U-EFFECTIVE = 0.26126
                CONSTRUCTION = CERAMIC-FLOOR  ..

CEILING1-5 =  INTERIOR-WALL
                AREA = 89.99
                TILT = 0
                NEXT-TO = SPACE-ATTIC
                CONSTRUCTION = GYPSUM-CEILING-2ND  ..


$ SPACE 1-6 :  SEMI-OUTDOOR   ******NOT USED******

SPACE1-6   =   SPACE
               SPACE-CONDITIONS  =  LIVING-SPACE
               PEOPLE-SCHEDULE   =  UNOCC1-6YEAR
               LIGHTING-SCHEDULE =  LIGHT1-6YEAR
               EQUIP-SCHEDULE    =  EQUIP1-6YEAR
               LIGHTING-KW       =  0
               EQUIPMENT-KW      =  0.260
               AREA              =  95.0332
               VOLUME            =  779.462  ..

BACK1-8    =   EXTERIOR-WALL
                WIDTH   = 10
                HEIGHT  = 7
                AZIMUTH = 0
                X = 30.851
                Y = 46.43
                Z = 0
                CONSTRUCTION = BRICK-WALL  ..

BACK1-9    =   EXTERIOR-WALL
                WIDTH   = 10
                HEIGHT  = 7
                AZIMUTH = 0
                X = 20.851
                Y = 46.43
                Z = 0
                CONSTRUCTION = BRICK-WALL  ..

BACK1-10    =   EXTERIOR-WALL
                WIDTH   = 0.341
                HEIGHT  = 7
                AZIMUTH = 0
                X = 10.851
                Y = 46.43
                Z = 0
```

```
                 CONSTRUCTION = BRICK-WALL  ..

$*********************************************************
$ SPACE1-3 : PLENUM
SPACE1-3 = SPACE
               SPACE-CONDITIONS   =  PLENUM-SPACE
               AREA               =  473.40
               VOLUME             =  1086.48  ..


RIGHT1-1P   =   EXTERIOR-WALL
                 WIDTH   = 12.139
                 HEIGHT  = 2.297
                 AZIMUTH = 90
                 X = 32.82     Y = 10.59
                 Z = 8.202
                 CONSTRUCTION = BRICK-WALL  ..

BACK1-7P   =   EXTERIOR-WALL
                 WIDTH   = 1.969
                 HEIGHT  = 2.297
                 AZIMUTH = 0
                 X = 32.82    Y = 22.729
                 Z = 8.202
                 CONSTRUCTION = BRICK-WALL  ..

RIGHT1-2P   =   EXTERIOR-WALL
                 WIDTH   = 6.562
                 HEIGHT  = 2.297
                 AZIMUTH = 90
                 X = 30.851
                 Y = 22.729
                 Z = 8.202
                 CONSTRUCTION = BRICK-WALL  ..

RIGHT1-4P   =   EXTERIOR-WALL
                 WIDTH   = 12.139
                 HEIGHT  = 2.297
                 AZIMUTH = 90
                 X = 30.851
                 Y = 29.291
                 Z = 8.202
                 CONSTRUCTION = BRICK-WALL  ..

BACK1-2P   =   EXTERIOR-WALL
                 WIDTH   = 10.499
                 HEIGHT  = 2.297
                 AZIMUTH = 0
                 X = 30.851    Y = 41.43
                 Z = 8.202
                 CONSTRUCTION = BRICK-WALL  ..

BACK1-1P   =   EXTERIOR-WALL
                 WIDTH   = 9.842
                 HEIGHT  = 2.297
                 AZIMUTH = 0
                 X = 20.351    Y = 41.43
                 Z = 8.202
                 CONSTRUCTION = BRICK-WALL  ..

LEFT1-3P    =   EXTERIOR-WALL
                 WIDTH   = 11.574
                 HEIGHT  = 2.297
                 AZIMUTH = 270
                 X = 10.51
                 Y = 41.43
                 Z = 8.202
                 CONSTRUCTION = BRICK-WALL  ..

LEFT1-4P    =   EXTERIOR-WALL
                 WIDTH   = 4.55
                 HEIGHT  = 2.297
                 AZIMUTH = 270
                 X = 10.51
                 Y = 34.406
                 Z = 8.202
                 CONSTRUCTION = BRICK-WALL  ..
```

```
LEFT1-1P    =   EXTERIOR-WALL
                 WIDTH   = 11.483
                 HEIGHT  = 2.297
                 AZIMUTH = 270
                 X = 19.696
                 Y = 22.073
                 Z = 8.202
                 CONSTRUCTION = BRICK-WALL  ..

FRONT1-1P   =   EXTERIOR-WALL
                 WIDTH   = 13.124
                 HEIGHT  = 2.297
                 AZIMUTH = 180
                 X = 19.696
                 Y = 10.59
                 Z = 8.202
                 CONSTRUCTION = BRICK-WALL  ..

$************************************************************
$ SPACE 2-1 :  MASTER BEDROOM
SPACE2-1   =   SPACE
               SPACE-CONDITIONS  =  LIVING-SPACE
               PEOPLE-SCHEDULE   =  OCC2-1YEAR
               LIGHTING-SCHEDULE =  LIGHT2-1YEAR
               EQUIP-SCHEDULE    =  EQUIP2-1YEAR
               LIGHTING-KW       =  0.064
               EQUIPMENT-KW      =  0.215
               AREA              =  270.33
               VOLUME            =  2217.212  ..

FRONT2-1    =   EXTERIOR-WALL
                 WIDTH   = 23.622
                 HEIGHT  = 8.202
                 AZIMUTH = 180
                 X = 9.198
                 Y = 10.59
                 Z = 10.499
                 CONSTRUCTION = BRICK-WALL  ..

WINDOW-F-2-1-1 = WINDOW
                  WIDTH   = 5.246
                  HEIGHT  = 2.949
                  X = 2.953
                  Y = 2.953
                 GLASS-TYPE = GLASS-2
                 SHADING-SCHEDULE = CURTAIN-2 $ ACCOUNTED FOR THE CURTAIN
                 FRAME-WIDTH = 0.33  ..


WINDOW-F-2-1-2 = WINDOW
                  WIDTH   = 4.42
                  HEIGHT  = 5.902
                  X = 13.292
                  Y = 0
                 GLASS-TYPE = GLASS-2
                 SHADING-SCHEDULE = CURTAIN-2 $ ACCOUNTED FOR THE CURTAIN
                 FRAME-WIDTH = 0.33  ..


RIGHT2-1    =   EXTERIOR-WALL
                 WIDTH   = 11.811
                 HEIGHT  = 8.202
                 AZIMUTH = 90
                 X = 32.82
                 Y = 10.59
                 Z = 10.499
                 CONSTRUCTION = BRICK-WALL  ..

WINDOW-R-2-1 = WINDOW
                WIDTH   = 2.293
                HEIGHT  = 2.949
                X = 4.593
                Y = 2.953
                 GLASS-TYPE = GLASS-2
                 SHADING-SCHEDULE = CURTAIN-2 $ ACCOUNTED FOR THE CURTAIN
                 FRAME-WIDTH = 0.33  ..
```

```
LEFT2-1    =   EXTERIOR-WALL
                 WIDTH   = 11.483
                 HEIGHT  = 8.202
                 AZIMUTH = 270
                 X = 9.198
                 Y = 22.073
                 Z = 10.499
                 CONSTRUCTION = BRICK-WALL  ..

WINDOW-L-2-1 = WINDOW
                WIDTH   = 2.293
                HEIGHT  = 2.949
                X = 3.681
                Y = 2.953
                 GLASS-TYPE = GLASS-2
                 SHADING-SCHEDULE = CURTAIN-2 $ ACCOUNTED FOR THE CURTAIN
                 FRAME-WIDTH = 0.33  ..


INTER2-1-A =   INTERIOR-WALL
                 AREA = 132.25
                 NEXT-TO = SPACE2-4
                 CONSTRUCTION = BRICK-WALL  ..

INTER2-1-B =   INTERIOR-WALL
                 AREA = 61.50
                 NEXT-TO = SPACE1-2
                 CONSTRUCTION = BRICK-WALL  ..

FLOOR2-1-A =   INTERIOR-WALL
                 AREA = 155
                 NEXT-TO = SPACE1-3
                 CONSTRUCTION = PARQUET-FLOOR  ..

FLOOR2-1-B =   EXTERIOR-WALL      $FLOOR ABOVE THE PARKING SPACE
                 WIDTH   = 10.412
                 HEIGHT  = 11.811
                 AZIMUTH = 180
                 TILT    = 180
                 X = 9.198
                 Y = 22.401
                 Z = 10.499
                 CONSTRUCTION = PARQUET-FLOOR  ..

CEILING2-1 =  INTERIOR-WALL
                 AREA = 270.33
                 TILT = 0
                 NEXT-TO = SPACE-ATTIC
                 CONSTRUCTION = GYPSUM-CEILING-2ND  ..


$ SPACE 2-2 :  BEDROOM 2
SPACE2-2   =   SPACE
               SPACE-CONDITIONS  =  LIVING-SPACE
               PEOPLE-SCHEDULE   =  OCC2-2YEAR
               LIGHTING-SCHEDULE =  LIGHT2-2YEAR
               EQUIP-SCHEDULE    =  EQUIP2-2YEAR
               LIGHTING-KW       =  0.032
               EQUIPMENT-KW      =  0.108
               AREA              =  131.87
               VOLUME            =  1081.504  ..

RIGHT2-3    =   EXTERIOR-WALL
                 WIDTH   = 11.811
                 HEIGHT  = 8.202
                 AZIMUTH = 90
                 X = 32.82
                 Y = 29.691
                 Z = 10.499
                 CONSTRUCTION = BRICK-WALL  ..

WINDOW-R-2-3 = WINDOW
                WIDTH   = 2.293
                HEIGHT  = 2.949
                X = 4.101
```

```
                Y = 2.953
                 GLASS-TYPE = GLASS-2
                 SHADING-SCHEDULE = CURTAIN-2 $ ACCOUNTED FOR THE CURTAIN
                 FRAME-WIDTH = 0.33  ..

BACK2-2    =   EXTERIOR-WALL
                 WIDTH   = 11.484
                 HEIGHT  = 8.202
                 AZIMUTH = 0
                 X = 32.82
                 Y = 41.43
                 Z = 10.499
                 CONSTRUCTION = BRICK-WALL  ..

WINDOW-B-2-2 = WINDOW
                WIDTH   = 4.586
                HEIGHT  = 2.949
                X = 3.445  Y = 2.953
                 GLASS-TYPE = GLASS-2
                 SHADING-SCHEDULE = CURTAIN-2 $ ACCOUNTED FOR THE CURTAIN
                 FRAME-WIDTH = 0.33  ..

INTER2-3-A =   INTERIOR-WALL
                 AREA = 67.27
                 NEXT-TO = SPACE2-4
                 CONSTRUCTION = BRICK-WALL  ..
INTER2-3-B =   INTERIOR-WALL
                 AREA = 26.92
                 NEXT-TO = SPACE2-4
                 CONSTRUCTION = BRICK-WALL  ..

INTER2-5   =   INTERIOR-WALL
                 AREA = 96.87
                 NEXT-TO = SPACE2-3
                 CONSTRUCTION = BRICK-WALL  ..

FLOOR2-2-A  =   INTERIOR-WALL
                 AREA = 112.382
                 NEXT-TO = SPACE1-3
                 CONSTRUCTION = PARQUET-FLOOR  ..

FLOOR2-2-B =   EXTERIOR-WALL      $CANTILEVERED FLOOR
                 WIDTH   = 1.969
                 HEIGHT  = 11.811
                 AZIMUTH = 180
                 TILT    = 180
                 X = 30.851
                 Y = 41.43
                 Z = 10.499
                 CONSTRUCTION = PARQUET-FLOOR  ..

CEILING2-2 =  INTERIOR-WALL
                 AREA = 131.87
                 TILT = 0
                 NEXT-TO = SPACE-ATTIC
                 CONSTRUCTION = GYPSUM-CEILING-2ND  ..


$ SPACE 2-3 :  BEDROOM 3
SPACE2-3   =   SPACE
               SPACE-CONDITIONS  =  LIVING-SPACE
               PEOPLE-SCHEDULE   =  OCC2-3YEAR
               LIGHTING-SCHEDULE =  LIGHT2-3YEAR
               EQUIP-SCHEDULE    =  EQUIP2-3YEAR
               LIGHTING-KW       =  0.032
               EQUIPMENT-KW      =  1.2
               AREA              =  278.76   $ Nominal value (100% larger) than the actual (139.38)
               AIR-CHANGES/HR    =  0.5            $ INDIVIDUAL
               VOLUME            =  2286.4  .. $ Nominal value (100% larger) than the actual
(1143.201)

BACK2-1    =   EXTERIOR-WALL
                 WIDTH   = 12.138
                 HEIGHT  = 8.202
                 AZIMUTH = 0
                 X = 21.336
                 Y = 41.43
```

```
                Z = 10.499
                CONSTRUCTION = BRICK-WALL  ..

WINDOW-B-2-1 = WINDOW
               WIDTH   = 4.586
               HEIGHT  = 2.949
               X = 1.969
               Y = 2.953
                GLASS-TYPE = GLASS-2
                SHADING-SCHEDULE = CURTAIN-2 $ ACCOUNTED FOR THE CURTAIN
                FRAME-WIDTH = 0.33  ..

LEFT2-3    =   EXTERIOR-WALL
                WIDTH   = 11.483
                HEIGHT  = 8.202
                AZIMUTH = 270
                X = 9.198
                Y = 41.43
                Z = 10.499
                CONSTRUCTION = BRICK-WALL  ..

WINDOW-L-2-3 = WINDOW
               WIDTH   = 2.289
               HEIGHT  = 2.949
               X = 4.757
               Y = 2.953
                GLASS-TYPE = GLASS-2
                SHADING-SCHEDULE = CURTAIN-2 $ ACCOUNTED FOR THE CURTAIN
                FRAME-WIDTH = 0.33  ..

FLOOR2-3-A  =   INTERIOR-WALL
                AREA = 129.64
                NEXT-TO = SPACE1-3
                CONSTRUCTION = PARQUET-FLOOR  ..

FLOOR2-3-B =   EXTERIOR-WALL      $CANTILEVERED FLOOR
                WIDTH   = 1.969
                HEIGHT  = 11.483
                AZIMUTH = 180
                TILT    = 180
                X = 9.198
                Y = 41.43
                Z = 10.499
                CONSTRUCTION = PARQUET-FLOOR  ..

INTER2-3   =   INTERIOR-WALL
                AREA = 150  $ Nominal value (actual is 75)
                NEXT-TO = SPACE1-2
                CONSTRUCTION = BRICK-WALL  ..


CEILING2-3 =  INTERIOR-WALL
                AREA = 139.38
                TILT = 0
                NEXT-TO = SPACE-ATTIC
                CONSTRUCTION = GYPSUM-CEILING-2ND  ..

$ SPACE 2-4 :  BATHROOM & 2ND FLOOR HALL
SPACE2-4   =   SPACE
               SPACE-CONDITIONS  =  LIVING-SPACE
               PEOPLE-SCHEDULE   =  UNOCC2-4YEAR
               LIGHTING-SCHEDULE =  LIGHT2-4YEAR
               EQUIP-SCHEDULE    =  EQUIP2-4YEAR
               LIGHTING-KW       =  0.064
               EQUIPMENT-KW      =  0.1
               AREA              =  90.00
               VOLUME            =  738.13  ..

RIGHT2-2    =   EXTERIOR-WALL
                WIDTH   = 7.218
                HEIGHT  = 8.202
                AZIMUTH = 90
                X = 32.82
                Y = 22.401
                Z = 10.499
                CONSTRUCTION = BRICK-WALL  ..
```

```
WINDOW-R-2-2 = WINDOW
                WIDTH   = 2.951
                HEIGHT  = 1.0
                X = 1.969
                Y = 5.232
                 GLASS-TYPE = GLASS-2
                 SHADING-SCHEDULE = CURTAIN-2 $ SANDED GLASS
                 FRAME-WIDTH = 0.33  ..

$INTER2-2   =   INTERIOR-WALL
$                 AREA = 59.20
$                 NEXT-TO = **THIS WALL IS IN THIS SPACE**
$                 CONSTRUCTION = BRICK-WALL  ..

FLOOR2-4-A  =   INTERIOR-WALL
                 AREA = 45
                 NEXT-TO = SPACE1-3
                 CONSTRUCTION = PARQUET-FLOOR  ..

FLOOR2-4-B  =   INTERIOR-WALL
                 AREA = 45
                 NEXT-TO = SPACE1-1
                 CONSTRUCTION = CERAMIC-FLOOR-2  ..

FLOOR2-4-C =   EXTERIOR-WALL      $CANTILEVERED FLOOR
                 WIDTH   = 7.218
                 HEIGHT  = 1.969
                 AZIMUTH = 90
                 TILT    = 180
                 X = 30.851
                 Y = 22.401
                 Z = 10.499
                 CONSTRUCTION = CERAMIC-FLOOR-2  ..

CEILING2-4 =  INTERIOR-WALL
                 AREA = 90.00
                 TILT = 0
                 NEXT-TO = SPACE-ATTIC
                 CONSTRUCTION = GYPSUM-CEILING-2ND  ..


$ SPACE-ATTIC : ATTIC
SPACE-ATTIC  = SPACE
               SPACE-CONDITIONS  =  ATTIC-SPACE
               AREA              =  1375.42
               VOLUME            =  3677.363  ..


FRONT-A-1    =  EXTERIOR-WALL
                 WIDTH   = 23.622  HEIGHT  = 2.297
                 AZIMUTH = 180  X = 9.198  Y = 10.59  Z = 18.701
                 SHADING-SURFACE = YES
                 CONSTRUCTION = BRICK-WALL  ..

RIGHT-A-1    =  EXTERIOR-WALL
                 WIDTH   = 30.84
                 HEIGHT  = 2.297
                 AZIMUTH = 90
                 X = 32.82
                 Y = 10.59
                 Z = 18.701
                 SHADING-SURFACE = YES
                 CONSTRUCTION = BRICK-WALL  ..

BACK-A-1     =  EXTERIOR-WALL
                 WIDTH   = 23.622
                 HEIGHT  = 2.297
                 AZIMUTH = 0
                 X = 32.82
                 Y = 41.43
                 Z = 18.701
                 SHADING-SURFACE = YES
                 CONSTRUCTION = BRICK-WALL  ..

LEFT-A-1     =  EXTERIOR-WALL
                 WIDTH   = 11.483
                 HEIGHT  = 2.297
```

```
                 AZIMUTH = 270
                 X = 9.198
                 Y = 41.43
                 Z = 18.701
                 SHADING-SURFACE = YES
                 CONSTRUCTION = BRICK-WALL  ..

BACK-A-2     =  EXTERIOR-WALL
                 WIDTH   = 1.969
                 HEIGHT  = 2.297
                 AZIMUTH = 0
                 X = 9.198
                 Y = 29.947
                 Z = 18.701
                 SHADING-SURFACE = YES
                 CONSTRUCTION = BRICK-WALL  ..

LEFT-A-2     =  EXTERIOR-WALL
                 WIDTH   = 7.874
                 HEIGHT  = 2.297
                 AZIMUTH = 270
                 X = 7.229
                 Y = 29.947
                 Z = 18.701
                 SHADING-SURFACE = YES
                 CONSTRUCTION = BRICK-WALL  ..

FRONT-A-2    =  EXTERIOR-WALL
                 WIDTH   = 1.969
                 HEIGHT  = 2.297
                 AZIMUTH = 180
                 X = 7.229
                 Y = 22.073
                 Z = 18.701
                 SHADING-SURFACE = YES
                 CONSTRUCTION = BRICK-WALL  ..

LEFT-A-3     =  EXTERIOR-WALL
                 WIDTH   = 11.483
                 HEIGHT  = 2.297
                 AZIMUTH = 270
                 X = 9.198
                 Y = 22.073
                 Z = 18.701
                 SHADING-SURFACE = YES
                 CONSTRUCTION = BRICK-WALL  ..

L-1          =  POLYGON (7.224,44.671,20.998) (7.224,6.979,20.998)
                     (21.834,21.588,29.414)(21.834,30.062,29.414) ..
ROOF-L-1     =  ROOF
                 POLYGON = L-1
                 CONSTRUCTION = CEMENT-ROOF1 ..

R-1          =  POLYGON (36.443,6.979,20.998) (36.443,44.671,20.998)
                 (21.834, 30.062, 29.414) (21.834,21.588,29.414)  ..

ROOF-R-1     =  ROOF
                 POLYGON = R-1
               $ AZIMUTH = 0  X=0 Y=0 Z=0
                 SHADING-SURFACE = YES
                 CONSTRUCTION = CEMENT-ROOF1 ..

B-1          =  POLYGON (36.443,44.671,20.998) (7.225,44.671,20.998)
                 (21.834, 30.062, 29.414)  ..

ROOF-B-1     =  ROOF
                 POLYGON = B-1
               $ AZIMUTH = 0  X=0 Y=0 Z=0
                 SHADING-SURFACE = YES
                 CONSTRUCTION = CEMENT-ROOF1 ..

F-1-a        =  POLYGON (7.224,6.979,20.998) (16.046,6.979,20.998)
                        (21.834,21.588,29.414)  ..

ROOF-F-1-a   =  ROOF
                 POLYGON = F-1-a
               $ AZIMUTH = 0  X=0 Y=0 Z=0
```

```
                 SHADING-SURFACE = YES
                 CONSTRUCTION = CEMENT-ROOF1 ..

F-1-b         =  POLYGON (16.046,6.979,20.998) (25.255,16.188,26.2675)
                        (21.834,21.588,29.414)  ..

ROOF-F-1-b   =  ROOF
                 POLYGON = F-1-b
               $ AZIMUTH = 0  X=0 Y=0 Z=0
                 SHADING-SURFACE = YES
                 CONSTRUCTION = CEMENT-ROOF1 ..

F-1-c         =  POLYGON (34.464,6.979,20.998) (21.834,21.588,29.414)
                         (25.255,16.188,26.2675)  ..

ROOF-F-1-c   =  ROOF
                 POLYGON = F-1-c
               $ AZIMUTH = 0  X=0 Y=0 Z=0
                 SHADING-SURFACE = YES
                 CONSTRUCTION = CEMENT-ROOF1 ..

F-1-d         =  POLYGON (34.464,6.979,20.998) (36.443,6.979,20.998)
                         (21.834,21.588,29.414)  ..

ROOF-F-1-d   =  ROOF
                 POLYGON = F-1-d
               $ AZIMUTH = 0  X=0 Y=0 Z=0
                 SHADING-SURFACE = YES
                 CONSTRUCTION = CEMENT-ROOF1 ..

F-2          =  POLYGON (16.046,2.058,20.998) (34.464,2.058,20.998)
                 (25.255,11.267,26.2675)  ..

ROOF-F-2     =  ROOF
                 POLYGON = F-2
               $ AZIMUTH = 0  X=0 Y=0 Z=0
                 SHADING-SURFACE = YES
                 CONSTRUCTION = CEMENT-ROOF1  ..

R-2          =  POLYGON (34.464,2.058,20.998) (34.464,6.979,20.998)
                 (25.255,16.188,26.2675) (25.255,11.267,26.2675)  ..

ROOF-R-2     =  ROOF
                 POLYGON = R-2
               $ AZIMUTH = 0  X=0 Y=0 Z=0
                 SHADING-SURFACE = YES
                 CONSTRUCTION = CEMENT-ROOF1  ..

L-2-a        =  POLYGON (16.046,2.058,20.998) (25.255,11.267,26.2675)
                        (16.046,6.979,20.998)  ..

ROOF-L-2-a   =  ROOF
                 POLYGON = L-2-a
               $ AZIMUTH = 0  X=0 Y=0 Z=0
                 SHADING-SURFACE = YES
                 CONSTRUCTION = CEMENT-ROOF1  ..

L-2-b        =  POLYGON (25.255,11.267,26.2675) (25.255,16.188,26.2675)
                         (16.046,6.979,20.998)  ..

ROOF-L-2-b   =  ROOF
                 POLYGON = L-2-b
               $ AZIMUTH = 0  X=0 Y=0 Z=0
                 SHADING-SURFACE = YES
                 CONSTRUCTION = CEMENT-ROOF1  ..

EX-CEILING-F1 =  EXTERIOR-WALL
                 WIDTH   = 27.245  HEIGHT  = 3.611
                 AZIMUTH = 180  TILT = 0
                 X=9.198  Y=6.979  Z=20.998
                 SHADING-SURFACE = YES
                 CONSTRUCTION = GYPSUM-CEILING-2ND  ..

EX-CEILING-F2 =  EXTERIOR-WALL
                 WIDTH   = 18.418  HEIGHT  = 4.921
                 AZIMUTH = 180  TILT = 0
                 X=16.046  Y=2.058  Z=20.998
```

```
                 SHADING-SURFACE = YES
                 CONSTRUCTION = GYPSUM-CEILING-2ND  ..

EX-CEILING-R1 =  EXTERIOR-WALL
                 WIDTH   = 30.84  HEIGHT  = 1.979
                 AZIMUTH = 90  TILT = 0
                 X=36.443  Y=10.59  Z=20.998
                 SHADING-SURFACE = YES
                 CONSTRUCTION = GYPSUM-CEILING-2ND  ..

EX-CEILING-B1 =  EXTERIOR-WALL
                 WIDTH   = 27.245  HEIGHT  = 3.241
                 AZIMUTH = 0  TILT = 0
                 X=36.443  Y=44.671  Z=20.998
                 SHADING-SURFACE = YES
                 CONSTRUCTION = GYPSUM-CEILING-2ND  ..

EX-CEILING-L1 =  EXTERIOR-WALL
                 WIDTH   = 14.724  HEIGHT  = 1.969
                 AZIMUTH = 270  TILT = 0
                 X=7.229  Y=44.671  Z=20.998
                 SHADING-SURFACE = YES
                 CONSTRUCTION = GYPSUM-CEILING-2ND  ..

EX-CEILING-L2 =  EXTERIOR-WALL
                 WIDTH   = 15.094  HEIGHT  = 1.969
                 AZIMUTH = 270  TILT = 0
                 X=7.229  Y=22.073  Z=20.998
                 SHADING-SURFACE = YES
                 CONSTRUCTION = GYPSUM-CEILING-2ND  ..


$ SPACE-ATTIC-2 : ATTIC
SPACE-ATTIC-2  = SPACE
               SPACE-CONDITIONS  =  ATTIC-SPACE-B
               AREA              =  500
               VOLUME            =  750  ..

INTER-ATT-1   =   INTERIOR-WALL
                 AREA = 400
                 NEXT-TO = SPACE-ATTIC
                 CONSTRUCTION = BRICK-WALL  ..

INTER-ATT-2   =   INTERIOR-WALL
                 AREA = 400
                 NEXT-TO = SPACE-ATTIC
                 CONSTRUCTION = BRICK-WALL  ..
INTER-ATT-3   =   INTERIOR-WALL
                 AREA = 400
                 NEXT-TO = SPACE-ATTIC
                 CONSTRUCTION = BRICK-WALL  ..


$*********************B U I L D I N G   S H A D E************************
$GROUP A: GARAGE

A-BACK-1     =  BUILDING-SHADE
                X=4.539  Y=22.073  Z=0  H=9.249  W=1.25
                AZ=0  TILT=90  ..

A-BACK-2     =  BUILDING-SHADE
                X=7.229  Y=22.073  Z=9.249  H=3.75  W=3.94
                AZ=0  TILT=90  ..

A-LEFT-1     =  BUILDING-SHADE
                X=3.289  Y=22.073  Z=0  H=9.249  W=1.25
                AZ=270  TILT=90  ..

A-LEFT-2     =  BUILDING-SHADE
                X=3.289  Y=22.073  Z=9.249  H=3.75  W=11.483
                AZ=270  TILT=90  ..

A-LEFT-3     =  BUILDING-SHADE
                X=3.289  Y=10.59  Z=0  H=10.499  W=4.265
                AZ=270  TILT=90  ..

$START LEFT TRIANGLE AREA
```

```
A-LEFT-4-1     =  BUILDING-SHADE
                X=3.289  Y=10.59  Z=10.499  H=0.301  W=3.7515
                AZ=270  TILT=90  ..

A-LEFT-4-2     =  BUILDING-SHADE
                X=3.289  Y=10.59  Z=10.8  H=0.2  W=3.4103
                AZ=270  TILT=90  ..

A-LEFT-4-3     =  BUILDING-SHADE
                X=3.289  Y=10.59  Z=11  H=0.2  W=3.0691
                AZ=270  TILT=90  ..

A-LEFT-4-4     =  BUILDING-SHADE
                X=3.289  Y=10.59  Z=11.2  H=0.2  W=2.7279
                AZ=270  TILT=90  ..

A-LEFT-4-5     =  BUILDING-SHADE
                X=3.289  Y=10.59  Z=11.4  H=0.2  W=2.3867
                AZ=270  TILT=90  ..

A-LEFT-4-6     =  BUILDING-SHADE
                X=3.289  Y=10.59  Z=11.6  H=0.2  W=2.0455
                AZ=270  TILT=90  ..

A-LEFT-4-7     =  BUILDING-SHADE
                X=3.289  Y=10.59  Z=11.8  H=0.2  W=1.7043
                AZ=270  TILT=90  ..

A-LEFT-4-8     =  BUILDING-SHADE
                X=3.289  Y=10.59  Z=12  H=0.2  W=1.3631
                AZ=270  TILT=90  ..

A-LEFT-4-9     =  BUILDING-SHADE
                X=3.289  Y=10.59  Z=12.2  H=0.2  W=1.0219
                AZ=270  TILT=90  ..

A-LEFT-4-10    =  BUILDING-SHADE
                X=3.289  Y=10.59  Z=12.4  H=0.2  W=0.6807
                AZ=270  TILT=90  ..

A-LEFT-4-11    =  BUILDING-SHADE
                X=3.289  Y=10.59  Z=12.6  H=0.2  W=0.3395
                AZ=270  TILT=90  ..

$END LEFT TRIANGLE AREA

A-LEFT-ROOF  =  BUILDING-SHADE
                X=3.289  Y=22.073  Z=11.6  H=6.0724  W=11.483
                AZ=270  TILT=13  ..

A-FRONT-1    =  BUILDING-SHADE
                X=3.289  Y=6.234  Z=0  H=9.249  W=1.25
                AZ=180  TILT=90  ..

A-FRONT-2    =  BUILDING-SHADE
                X=3.289  Y=6.234  Z=9.249  H=1.25  W=16.407
                AZ=180  TILT=90  ..

A-FRONT-ROOF =  BUILDING-SHADE
                X=3.289  Y=6.234  Z=10.499  H=4.93  W=16.407
                AZ=180  TILT=30  ..

A-RIGHT-1    =  BUILDING-SHADE
                X=19.696  Y=6.234  Z=9.249  H=1.25  W=4.265
                AZ=90  TILT=90  ..

$START RIGHT TRIANGLE AREA

A-RIGHT-2-1     =  BUILDING-SHADE
                X=19.696  Y=6.7475  Z=10.499  H=0.301  W=3.7515
                AZ=90  TILT=90  ..

A-RIGHT-2-2    =  BUILDING-SHADE
                X=19.696  Y=7.0938  Z=10.8  H=0.2  W=3.4103
                AZ=90  TILT=90  ..
```

```
A-RIGHT-2-3    =  BUILDING-SHADE
                X=19.696  Y=7.435  Z=11  H=0.2  W=3.0691
                AZ=90  TILT=90  ..

A-RIGHT-2-4     =  BUILDING-SHADE
                X=19.696  Y=7.7762  Z=11.2  H=0.2  W=2.7279
                AZ=90  TILT=90  ..

A-RIGHT-2-5     =  BUILDING-SHADE
                X=19.696  Y=8.1174  Z=11.4  H=0.2  W=2.3867
                AZ=90  TILT=90  ..

A-RIGHT-2-6     =  BUILDING-SHADE
                X=19.696  Y=8.4586  Z=11.6  H=0.2  W=2.0455
                AZ=90  TILT=90  ..

A-RIGHT-2-7     =  BUILDING-SHADE
                X=19.696  Y=8.7998  Z=11.8  H=0.2  W=1.7043
                AZ=90  TILT=90  ..

A-RIGHT-2-8     =  BUILDING-SHADE
                X=19.696  Y=9.141  Z=12  H=0.2  W=1.3631
                AZ=90  TILT=90  ..

A-RIGHT-2-9     =  BUILDING-SHADE
                X=19.696  Y=9.4822  Z=12.2  H=0.2  W=1.0219
                AZ=90  TILT=90  ..

A-RIGHT-2-10    =  BUILDING-SHADE
                X=19.696  Y=9.8234  Z=12.4  H=0.2  W=0.6807
                AZ=90  TILT=90  ..

A-RIGHT-2-11    =  BUILDING-SHADE
                X=19.696  Y=10.1646  Z=12.6  H=0.2  W=0.3395
                AZ=90  TILT=90  ..

$END RIGHT TRIANGLE AREA

$GROUP B: PILLAR AND BALCONY

$PILLAR

B-FRONT-1-1    =  BUILDING-SHADE
                  X=19.696  Y=5.667  Z=0  H=20.998  W=1.3125
                  AZ=180  TILT=90  ..

B-RIGHT-1-1    =  BUILDING-SHADE
                  X=21.0085  Y=5.667  Z=0  H=20.998  W=1.3125
                  AZ=90  TILT=90  ..

B-LEFT-1-1    =  BUILDING-SHADE
                  X=19.696  Y=6.9795  Z=0  H=20.998  W=1.3125
                  AZ=270  TILT=90  ..

B-FRONT-1-2    =  BUILDING-SHADE
                  X=29.536  Y=5.667  Z=0  H=20.998  W=1.3125
                  AZ=180  TILT=90  ..

B-RIGHT-1-2    =  BUILDING-SHADE
                  X=30.8485  Y=5.667  Z=0  H=20.998  W=1.3125
                  AZ=90  TILT=90  ..

B-LEFT-1-2    =  BUILDING-SHADE
                  X=29.536  Y=6.9795  Z=0  H=20.998  W=1.3125
                  AZ=270  TILT=90  ..

$BALCONY

B-PIECE-1    =  BUILDING-SHADE
                  X=20.202  Y=10.590  Z=9.25  H=4.25  W=1.974
                  AZ=248  TILT=90  ..

B-PIECE-2    =  BUILDING-SHADE
                  X=20.929  Y=8.755  Z=9.25  H=4.25  W=1.809
                  AZ=228  TILT=90  ..

B-PIECE-3    =  BUILDING-SHADE
```

```
                  X=22.148  Y=7.417  Z=9.25  H=4.25  W=1.762
                  AZ=202  TILT=90  ..

B-PIECE-4    =  BUILDING-SHADE
                  X=23.703  Y=6.589  Z=9.25  H=4.25  W=1.679
                  AZ=193  TILT=90  ..

B-PIECE-5    =  BUILDING-SHADE
                  X=25.360  Y=6.320  Z=9.25  H=4.25  W=1.679
                  AZ=171  TILT=90  ..

B-PIECE-6    =  BUILDING-SHADE
                  X=27.017  Y=6.589  Z=9.25  H=4.25  W=1.762
                  AZ=152  TILT=90  ..

B-PIECE-7    =  BUILDING-SHADE
                  X=28.572  Y=7.417  Z=9.25  H=4.25  W=1.809
                  AZ=132  TILT=90  ..

B-PIECE-8    =  BUILDING-SHADE
                  X=29.791  Y=8.755  Z=9.25  H=4.25  W=1.974
                  AZ=112  TILT=90  ..

B-FLOOR-P-1  =  BUILDING-SHADE
                  X=20.929  Y=8.755  Z=9.25  H=1.835  W=8.862
                  AZ=180  TILT=0  ..

B-FLOOR-P-2  =  BUILDING-SHADE
                  X=22.148  Y=7.417  Z=9.25  H=1.338  W=6.424
                  AZ=180  TILT=0  ..

B-FLOOR-P-3  =  BUILDING-SHADE
                  X=23.703  Y=6.589  Z=9.25  H=0.828  W=3.314
                  AZ=180  TILT=0  ..

$GROUP C: FENCE AND ADJACENT BUILDING

C-LEFT-1    =  BUILDING-SHADE
                  X=0  Y=46.09  Z=0  H=5  W=46.09
                  AZ=270  TILT=90  ..

C-LEFT-2    =  BUILDING-SHADE
                  X=0  Y=46.09  Z=5  H=5  W=40
                  AZ=270  TILT=90  ..

C-LEFT-3-1  =  BUILDING-SHADE    $Profile of the house on the west
                  X=-19.691  Y=44.6701 Z=0  H=20.998  W=42.613
                  AZ=270  TILT=90  ..

C-LEFT-3-2A  =  BUILDING-SHADE    $Profile of the house on the west
                  X=-19.691  Y=37.062  Z=20.998  H=4.416  W=27.613
                  AZ=270  TILT=90  ..

C-LEFT-3-2B  =  BUILDING-SHADE    $Profile of the house on the west
                  X=-19.691  Y=40.062  Z=20.998  H=2.416  W=3
                  AZ=270  TILT=90  ..
C-LEFT-3-2C  =  BUILDING-SHADE    $Profile of the house on the west
                  X=-19.691  Y=9.449  Z=20.998  H=2.416  W=3.5
                  AZ=270  TILT=90  ..

C-LEFT-3-3A  =  BUILDING-SHADE    $Profile of the house on the west
                  X=-19.691  Y=30.062  Z=25.414  H=4  W=8.474
                  AZ=270  TILT=90  ..

C-LEFT-3-3B  =  BUILDING-SHADE    $Profile of the house on the west
                  X=-19.691  Y=33.062  Z=25.414  H=2  W=3
                  AZ=270  TILT=90  ..

C-LEFT-3-3C  =  BUILDING-SHADE    $Profile of the house on the west
                  X=-19.691  Y=21.588  Z=25.414  H=2  W=3
                  AZ=270  TILT=90  ..

C-BACK-1    =  BUILDING-SHADE
                  X=39.068  Y=46.09  Z=0  H=5  W=39.068
                  AZ=0  TILT=90  ..

C-BACK-2    =  BUILDING-SHADE
```

```
                  X=30.851  Y=46.09  Z=5  H=4  W=20.341
                  AZ=0  TILT=90  ..

C-BACK-3    =  BUILDING-SHADE     $ROOF
                  X=30.851  Y=46.09  Z=9  H=4.7  W=20.341
                  AZ=0  TILT=15  ..

C-RIGHT-1A    =  BUILDING-SHADE
                  X=39.068  Y=4  Z=0  H=2  W=42.099
                  AZ=90  TILT=90  ..

C-RIGHT-1B    =  BUILDING-SHADE
                  X=39.068  Y=4  Z=2  H=3  W=42.099
                  TR=0.8  AZ=90  TILT=90  ..

C-FRONT-1A    =  BUILDING-SHADE
                  X=0  Y=0  Z=0  H=2  W=3.943
                  AZ=180  TILT=90  ..

C-FRONT-1B    =  BUILDING-SHADE
                  X=0  Y=0  Z=2  H=3  W=3.943
                  TR=0.8  AZ=180  TILT=90  ..

C-FRONT-2A    =  BUILDING-SHADE
                  X=19.696  Y=0  Z=0  H=2  W=16.1165
                  AZ=180  TILT=90  ..

C-FRONT-2B    =  BUILDING-SHADE
                  X=19.696  Y=0  Z=2  H=3  W=16.1165
                  TR=0.8  AZ=180  TILT=90  ..

C-FRONT-3A    =  BUILDING-SHADE
                  X=35.8125  Y=0  Z=0  H=2  W=5.0
                  AZ=130  TILT=90  ..

C-FRONT-3B    =  BUILDING-SHADE
                  X=35.8125  Y=0  Z=2  H=3  W=5.0
                  TR=0.8  AZ=130  TILT=90  ..

C-FRONT-4     =  BUILDING-SHADE    $Profile of the house on the south
                  X=-150  Y=-42 Z=0  H=29  W=187
                  AZ=180  TILT=90  ..

C-RIGHT-2     =  BUILDING-SHADE    $Profile of the house on the east
                  X=96  Y=-80 Z=0  H=29  W=120
                  AZ=90  TILT=90  ..

C-RIGHT-3     =  BUILDING-SHADE    $Profile of the house on the east
                  X=37  Y=-126 Z=0  H=29  W=84
                  AZ=90  TILT=90  ..

C-FRONT-5     =  BUILDING-SHADE    $Profile of the house on the south
                  X=37  Y=-126 Z=0  H=29  W=187
                  AZ=180  TILT=90  ..


$GROUP D: TREES AND BUSHES

D-RIGHT-1    =  BUILDING-SHADE
                  X=35.15  Y=6.856  Z=2.5  H=8  W=37.21
                  TR=0.2  AZ=90  TILT=90  ..

D-RIGHT-2    =  BUILDING-SHADE
                  X=35.15  Y=16  Z=2  H=24.998  W=12
                  TR=0.1  AZ=90  TILT=90  ..

D-FRONT-1    =  BUILDING-SHADE
                  X=30.54  Y=3.09  Z=2  H=10  W=8
                  TR=0.1  AZ=135  TILT=90  ..

B-FRONT-2    =  BUILDING-SHADE
                  X=19.696  Y=4.667  Z=0  H=6  W=8
                  TR=0.1  AZ=180  TILT=90  ..

$GROUP E: ROOF OVERHANG (PART OF THE ROOF)
$         AND SPACE2-1'S SHADING TO THE 1ST FLOOR
```

```
EX-CEILING-F1-SH =  BUILDING-SHADE
                 WIDTH   = 27.245  HEIGHT  = 3.611
                 AZIMUTH = 180  TILT = 0
                 X=9.198  Y=6.979  Z=21.008
                 TR=0.0  ..

EX-CEILING-F2-SH =  BUILDING-SHADE
                 WIDTH   = 18.418  HEIGHT  = 4.921
                 AZIMUTH = 180  TILT = 0
                 X=16.046  Y=2.058  Z=21.008
                 TR=0.0  ..

EX-CEILING-R1-SH =  BUILDING-SHADE
                 WIDTH   = 30.84  HEIGHT  = 3.623
                 AZIMUTH = 90  TILT = 0
                 X=36.443  Y=10.59  Z=21.008
                 TR=0.0  ..

EX-CEILING-B1-SH =  BUILDING-SHADE
                 WIDTH   = 27.245  HEIGHT  = 3.241
                 AZIMUTH = 0  TILT = 0
                 X=36.443  Y=44.671  Z=21.008
                 TR=0.0  ..

EX-CEILING-L1-SH =  BUILDING-SHADE
                 WIDTH   = 14.724  HEIGHT  = 1.969
                 AZIMUTH = 270  TILT = 0
                 X=7.229  Y=44.671  Z=21.008
                 TR=0.0  ..

EX-CEILING-L2-SH =  BUILDING-SHADE
                 WIDTH   = 15.094  HEIGHT  = 1.969
                 AZIMUTH = 270  TILT = 0
                 X=7.229  Y=22.073  Z=21.008
                 TR=0.0  ..

FLOOR2-1-B-SH =  BUILDING-SHADE    $FLOOR ABOVE THE PARKING SPACE
                 WIDTH   = 10.412  HEIGHT  = 11.811
                 AZIMUTH = 180  TILT = 0
                 X = 9.198  Y = 10.59  Z = 10.509
                 TR=0.0  ..

WALL1-2-B-SH  = BUILDING-SHADE    $NORTH WALL 2ND FLOOR OF SPACE1-2
                 WIDTH   = 1.969   HEIGHT  = 8.202
                 AZIMUTH = 0
                 X = 9.198  Y = 29.947  Z = 10.499
                 TR=0.0  ..


$************************BLOCK REPORTS**********************************

$ WINDOW-F-2-1-2 is a south facing window of SPACE2-1

W1  =  REPORT-BLOCK  VARIABLE-TYPE = WINDOW-F-2-1-2
                     VARIABLE-LIST = (1,14,15,16,17)  ..

H-REPORT-2 = H-R    R-SCH=SCH-1  R-B=(W1) ..


$ WINDOW-F-1-1 is a south facing window of SPACE1-1

W2  =  REPORT-BLOCK  VARIABLE-TYPE = WINDOW-F-1-1
                     VARIABLE-LIST = (1,14,15,16,17)  ..

H-REPORT-3 = H-R    R-SCH=SCH-1  R-B=(W2) ..

$ V-L (Window)= 1  = Window U-value (includes inside and outside film
$                    coefficients) (Btu/hr.sq.ft F)
$ V-L (Window)= 14 = Solar energy absorbed by glass and conducted into the
$                    space divided by window area, before multiplication by
$                    shading coefficient (Btu/hr.sq.ft)
$ V-L (Window)= 15 = Heat gain through window by solar radiation (Btu/hr)
$ V-L (Window)= 16 = Shading coefficient
$ V-L (Window)= 17 = Heat gain through window by conduction (Btu/hr)
```

```
$*************************************************************************


END  ..
COMPUTE LOADS   ..


$*************************  S  Y  S  T  E  M  ****************************

INPUT SYSTEMS  ..

SYSTEMS-REPORT    VERIFICATION =  (SV-A)
                  SUMMARY = (SS-A,SS-B,SS-C,SS-D,SS-J)  ..

$****************************SYSTEM PARAMETERS*************************************************

PARAMETER
$     P-HIR=1.25                          HIR = 1/AFUE(ANNUAL FUEL UTILIZATION EFFICIENCY
$                                          e.g.  AFUE = 80% --> HIR = 1.25
$                                        TURN OFF TO GO TO FUNCTION, 05/25/2003, S.KIM

$     P-EIR=0.341                         EIR = 3.41/SEER (SEASONAL ENERGY EFFICIENCY RATIO)
$                                          e.g.  SEER = 10  --> EIR = 0.341
$                                        TURN OFF TO GO TO FUNCTION, 05/25/2003, S.KIM

$     P-COOLINGCAPACITY = 0               $PARAMETER FOR COOLING CAPACITY, IF THE VALUE IS 0 OR
$                                          THE KEYWORD IS UNDEFINED THE SYSTEM IS AUTOSIZED BY
$                                          DOE-2.
$     P-HEATINGCAPACITY = 0               $PARAMETER FOR HEATING CAPACITY, IF THE VALUE IS 0 OR
$                                          THE KEYWORD IS UNDEFINED THE SYSTEM IS AUTOSIZED BY
$                                          DOE-2.


$************************ADD FUNCTION FOR DIFFERENT SYSTEM, 05/20/2003, S.KIM********************


            P-HEAT-SOURCE = ELECTRIC        $ COMMAND IN SYSTEM, 5/20/2003, S.KIM
            P-DHW-TYPE = ELEC-DHW-HEATER    $ COMMAND IN PLANT-ASSIGNMENT, 5/20/2003, S.KIM
            P-HIR=1                         $ COMMAND IN SYSTEM-EQUIPMENT
                                            $ ASSUME ELECTRIC STRIP HEAT EFFICIENCY = 1
                                            $ REDEFINITION BY S.KIM, 05/25/2003, S.KIM
                                            $ HIR = 3.41/HSPF (HEATING SEASONAL PERFORMANCE FACTOR
FOR HEAT-PUMP
                                            $ e.g.  HSPF = 6.8 --> HIR = 0.50
            P-EIR=0.341                     $ COMMAND IN SYSTEM-EQUIPMENT
                                            $ EIR = 3.41/SEER (SEASONAL ENERGY EFFICIENCY RATIO)
                                            $ e.g.  SEER = 10  --> EIR = 0.341
            P-FIR=1.25                      $ COMMAND IN SYSTEM-EQUIPMENT
                                            $ NOT USED AT THIS SYSTEM, BUT SHOULD ACTIVATE FOR
FUNCTION
                                            $ 05/25/2003, S.KIM
                 ..                         $END OF SYSTEM PARAMETERS



$ HEATING & COOLING SCHEDULES -SHUTDOWN
DAY-SHUT   =  DAY-SCHEDULE  (1,24) (0)  ..
WEEK-SHUT  =  WEEK-SCHEDULE (ALL) DAY-SHUT  ..
YEAR-SHUT  =  SCHEDULE  THRU DEC 31
              WEEK-SCHEDULE = WEEK-SHUT  ..

$ COOLING SCHEDULE
$ SPACE2-1: BEDROOM 1
COOL2-1WD  =  DAY-SCHEDULE  (1,7) (1) (8,18) (0) (19,24) (1)  ..
COOL2-1WE  =  DAY-SCHEDULE  (1,7) (1) (8,18) (0) (19,24) (1)  ..
COOL2-1WEEK  =  WEEK-SCHEDULE
         (WD) COOL2-1WD  (WEH) COOL2-1WE  ..
VACA-WD  =  DAY-SCHEDULE  (1,24) (0)  ..
VACA-WE  =  DAY-SCHEDULE  (1,24) (0)  ..
ON-VACATION  =  WEEK-SCHEDULE
         (WD) VACA-WD    (WEH) VACA-WE  ..
COOL2-1YEAR  =  SCHEDULE
         THRU JUL 10 WEEK-SCHEDULE = COOL2-1WEEK
         THRU JUL 15 WEEK-SCHEDULE = ON-VACATION
```

```
         THRU DEC 31 WEEK-SCHEDULE = COOL2-1WEEK  ..

$ SPACE2-2: BEDROOM 2
COOL2-2WD  =  DAY-SCHEDULE  (1,7) (0) (8,18) (0) (19,24) (0)  ..
COOL2-2WE  =  DAY-SCHEDULE  (1,7) (1) (8,18) (0) (19,24) (1)  ..
COOL2-2WEEK  =  WEEK-SCHEDULE
         (WD) COOL2-2WD  (WEH) COOL2-2WE  ..
COOL2-2YEAR  =  SCHEDULE
         THRU DEC 31  WEEK-SCHEDULE = COOL2-2WEEK  ..

$ THERMOSTAT SCHEDULE

     $ HEATING THERMOSTAT SCHEDULE FOR ALL ZONES (NO HEATING)
TDAY-HEAT   =  DAY-SCHEDULE  (1,24) (55)  ..  $ 12.78 C (SHUT DOWN)
TWEEK-HEAT  =  WEEK-SCHEDULE (ALL) TDAY-HEAT  ..
TYEAR-HEAT  =  SCHEDULE  THRU DEC 31
              WEEK-SCHEDULE = TWEEK-HEAT  ..

     $ COOLING THERMOSTAT SCHEDULE
$ SPACE2-1: BEDROOM 1
TCOOL2-1WD   =  DAY-SCHEDULE
               (1,7) (79.8) (8,18) (99) (19,24) (79.8)  ..
TCOOL2-1WE   =  DAY-SCHEDULE
               (1,7) (79.8) (8,18) (99) (19,24) (79.8)  ..
TCOOL2-1WEEK   =  WEEK-SCHEDULE
            (WD) TCOOL2-1WD  (WEH) TCOOL2-1WE ..
TCOOL2-1YEAR  =  SCHEDULE  THRU DEC 31
              WEEK-SCHEDULE = TCOOL2-1WEEK  ..

$ SPACE2-2: BEDROOM 2
TCOOL2-2WD   =  DAY-SCHEDULE
               (1,7) (99) (8,18) (99) (19,24) (99)  ..
TCOOL2-2WE   =  DAY-SCHEDULE
               (1,7) (80.6) (8,18) (99) (19,24) (80.6)  ..
TCOOL2-2WEEK   =  WEEK-SCHEDULE
            (WD) TCOOL2-2WD  (WEH) TCOOL2-2WE ..
TCOOL2-2YEAR  =  SCHEDULE  THRU DEC 31
              WEEK-SCHEDULE = TCOOL2-2WEEK  ..

$ FOR SPACE1-2, SPACE1-3, SPACE1-6, SPACE2-3, SPACE2-4, SPACE-STTIC
TCOOL-WD   =  DAY-SCHEDULE
               (1,7) (150) (8,18) (150) (19,24) (150)  ..
TCOOL-WE   =  DAY-SCHEDULE
               (1,7) (150) (8,18) (150) (19,24) (150)  ..
TCOOL-WEEK   =  WEEK-SCHEDULE
            (WD) TCOOL-WD  (WEH) TCOOL-WE ..
TCOOL-YEAR  =  SCHEDULE  THRU DEC 31
              WEEK-SCHEDULE = TCOOL-WEEK  ..

DHWSCH-1  =SCHEDULE   THRU DEC 31 (ALL)
              (1,7)(0) (8) (0.33) (9,18)(0)
              (19)(0.33)(20,24)(0) .. $Schedule from survey data of occupants


     $ COOLING THERMOSTAT SCHEDULE FOR A/C UNUSED ZONES

$ ZONE-CONTROL

  RESIDENTIAL-ZONE = ZONE-CONTROL
     DESIGN-HEAT-T  =  55              $NO HEATING
     HEAT-TEMP-SCH  =  TYEAR-HEAT      $NO HEATING
     DESIGN-COOL-T  =  78.8            $26 C
    $COOL-TEMP-SCH  =  INDIVIDULE
     THERMOSTAT-TYPE  =  TWO-POSITION  ..  $ ON/OFF ?THERMOSTAT-TYPE
    $THROTTLING-RANGE =   0.5  ..        IT'S A DEFULT FOR RESYS.

     $ CONDITIONED ZONES
          SPACE2-1  =  ZONE
              ZONE-TYPE       =  CONDITIONED
              ZONE-CONTROL    =  RESIDENTIAL-ZONE
              COOL-TEMP-SCH   =  TCOOL2-1YEAR
              SIZING-OPTION   =  ADJUST-LOADS   ..

          SPACE2-2  =  ZONE
              ZONE-TYPE       =  CONDITIONED
              ZONE-CONTROL    =  RESIDENTIAL-ZONE
              COOL-TEMP-SCH   =  TCOOL2-2YEAR
```

```
            SIZING-OPTION   =  ADJUST-LOADS   ..

     $ UNCONDITIONED ZONES

          SPACE1-1  =  ZONE
              ZONE-TYPE       =  CONDITIONED
              ZONE-CONTROL    =  RESIDENTIAL-ZONE
              COOL-TEMP-SCH   =  TCOOL-YEAR
              SIZING-OPTION   =  ADJUST-LOADS   ..

          SPACE1-2  =  ZONE
              ZONE-TYPE       =  CONDITIONED
              ZONE-CONTROL    =  RESIDENTIAL-ZONE
              COOL-TEMP-SCH   =  TCOOL-YEAR
              SIZING-OPTION   =  ADJUST-LOADS   ..

          SPACE1-3  =  ZONE
              ZONE-TYPE       =  CONDITIONED
              ZONE-CONTROL    =  RESIDENTIAL-ZONE
              COOL-TEMP-SCH   =  TCOOL-YEAR
              SIZING-OPTION   =  ADJUST-LOADS   ..

          SPACE1-6  =  ZONE
              ZONE-TYPE       =  CONDITIONED
              ZONE-CONTROL    =  RESIDENTIAL-ZONE
              COOL-TEMP-SCH   =  TCOOL-YEAR
              SIZING-OPTION   =  ADJUST-LOADS   ..

          SPACE2-3  =  ZONE
              ZONE-TYPE       =  CONDITIONED
              ZONE-CONTROL    =  RESIDENTIAL-ZONE
              COOL-TEMP-SCH   =  TCOOL-YEAR
              SIZING-OPTION   =  ADJUST-LOADS   ..

          SPACE2-4  =  ZONE
              ZONE-TYPE       =  CONDITIONED
              ZONE-CONTROL    =  RESIDENTIAL-ZONE
              COOL-TEMP-SCH   =  TCOOL-YEAR
              SIZING-OPTION   =  ADJUST-LOADS   ..

     $ PLENUM

         $SPACE-PLENUM  =  ZONE
             $ZONE-TYPE       =  PLENUM
               $SIZING-OPTION = ADJUST-LOADS
               $DESIGN-HEAT-T = 50
               $DESIGN-COOL-T = 99  ..

     $ ATTIC (DEFINED AS UNCONDITION ZONES)

          SPACE-ATTIC   =  ZONE
              ZONE-TYPE       =  CONDITIONED
              ZONE-CONTROL    =  RESIDENTIAL-ZONE
              COOL-TEMP-SCH   =  TCOOL-YEAR
              SIZING-OPTION   =  ADJUST-LOADS   ..

          SPACE-ATTIC-2 =  ZONE
              ZONE-TYPE       =  CONDITIONED
              ZONE-CONTROL    =  RESIDENTIAL-ZONE
              COOL-TEMP-SCH   =  TCOOL-YEAR
              SIZING-OPTION   =  ADJUST-LOADS   ..


$ SYSTEMS

    $SYSTEM FOR SPACE2-1
       SYS2-1 = SYSTEM
                SYSTEM-TYPE       =  RESYS
                ZONE-NAMES        =  (SPACE2-1)
                MAX-SUPPLY-T      =  77.05
                MIN-SUPPLY-T      =  70.0
              HEATING-SCHEDULE    =  YEAR-SHUT   $ NO HEATING
                HEATING-CAPACITY  =  0           $ NO HEATING
                HEAT-SOURCE       =  ELECTRIC    $ NO HEATING
              COOLING-SCHEDULE    =  COOL2-1YEAR
                COOLING-CAPACITY  =  17401
                COOLING-EIR       =  0.325  ..
```

```
$ NOTE***********************************************
$ DATA FROM THE AIR-CONDTIONING SYSTEM'S MANUFACTURE
$ BRAND: DAIKIN, MODEL: FT18GV1LS
$ SEER = 10.5
$ COOLING-EIR = 3.41/SEER = 3.412/10.5 = 0.325
$ NOTE***********************************************

    $SYSTEM FOR SPACE2-2
       SYS2-2 = SYSTEM
                SYSTEM-TYPE       =  RESYS
                ZONE-NAMES        =  (SPACE2-2)
                MAX-SUPPLY-T      =  77.05
                MIN-SUPPLY-T      =  70.0
              HEATING-SCHEDULE    =  YEAR-SHUT   $ NO HEATING
                HEATING-CAPACITY  =  0           $ NO HEATING
                HEAT-SOURCE       =  ELECTRIC    $ NO HEATING
              COOLING-SCHEDULE    =  COOL2-2YEAR
                COOLING-CAPACITY  =  12000
                COOLING-EIR       =  0.325  ..

$ NOTE***********************************************
$ DATA FROM THE AIR-CONDTIONING SYSTEM'S MANUFACTURE
$ BRAND: CARRIER, MODEL: 42RS012
$ SEER = 10.5
$ COOLING-EIR = 3.41/SEER = 3.41/10.5 = 0.325
$ NOTE***********************************************

    $SYSTEM FOR SPACE1-1, SPACE1-2, SPACE1-3, SPACE1-6, SPACE2-3, SPACE2-4,
$ SPACE-ATTIC AND SPACE-ATTIC-2
    SYS-UNCON = SYSTEM
                SYSTEM-TYPE       =  RESYS
                ZONE-NAMES        =  (SPACE1-1,SPACE1-2,SPACE1-3,
SPACE1-6,SPACE2-3,SPACE2-4,SPACE-ATTIC,SPACE-ATTIC-2)
                MAX-SUPPLY-T      =  77.05
                MIN-SUPPLY-T      =  70.0
              HEATING-SCHEDULE    =  YEAR-SHUT   $ NO HEATING
                HEATING-CAPACITY  =  0           $ NO HEATING
                HEAT-SOURCE       =  ELECTRIC    $ NO HEATING
              COOLING-SCHEDULE    =  YEAR-SHUT
                COOLING-CAPACITY  =  60000
                COOLING-EIR       =  0.325  ..


$ ***********************************PLANT ASSIGNMENT****************************************


PLANT1 = PLANT-ASSIGNMENT  SYSTEM-NAMES = (SYS2-1, SYS2-2,SYS-UNCON)

$           PLANT-REPORTS = YES                     DOE-2 DEFAULT
            MAX-FLUID-T = 110                      $DOE-2 DEFAULT(50 TO 120)(DEG F)
            MIN-FLUID-T = 75                       $DOE-2 DEFAULT(40 TO 80)(DEG F)
$           FLUID-VOLUME = 15                       UNUSED,DOE-2 DEFAULT(1 TO 500)(GAL/TON)
            DHW-TYPE = ELECTRIC                    $DOE-2 DEFAULT(OR ELECTRIC, HEAT PUMP,
$                                                   DESUPERHEAT,WASTE-HEAT)
$                                                   S.KIM,05/20/2003, ADD PARAMETER FOR MACRO
$           DHW-FLOW =                              UNUSED(LITRES/MIN)(OR DHW-GAL/MIN)
            DHW-SCH = DHWSCH-1
$           DHW-INLET-T-SCH =                       UNUSED, DEFAULT=MONTHLY GND TEMP FROM THE
$                                                   WEATHER TAPE
            DHW-SUPPLY-T = 110                     $SHOWERING FROM STEIN AND REYNOLD (1992)
$           DHW-GAL/MIN  = .0278                    CALCULATED FROM IECC 2001(402.1.3.7)
            DHW-GAL/MIN  = 1.875                   $ESTIMATED FROM CASE STUDY HOUSE DHW USEGE
$           DHW-SIZE =                              UNUSED(0 TO 1000)(GAL)
$           DHW-HEAT-RATE =                         UNUSED(0 TO 100000)(BTU/HR)
            DHW-EIR = 1                            $DOE-2 DEFAULT IS 1.39 FOR GAS,
$                                                   FOR ELECTRIC = 1 (0 TO 3)
            DHW-LOSS = 0                           $DOE-2 DEFAULT,(0 TO 1)
$           DHW-EIR-FT =                            UNUSED
$           DHW-HEAT-RATE-FT =                      UNUSED,DOE-2 DEFAULT
$           DHW-EIR-FPLR =                          UNUSED,DOE-2 DEFAULT
            DHW-PUMP-ELEC = 0.02                    $DOE-2 DEFAULT(0 TO 0.1)(W/BTU)
            DHW-PUMP-SCH = DHWSCH-1
$           DHW-HSUP-RATE =                         UNUSED(0 TO 100000)(BTU/HR)
$           DHW-HSTOR-RATE =                        UNUSED(0 TO 100000)(BTU/HR)
                            ..                     $END OF THE PLANT ASSIGNMENT COMMAND
```

```
HR-SCH-SYS   = SCHEDULE THRU DEC 31 (ALL) (1,24) (1)  ..

SREP-SYS1-1  =  REPORT-BLOCK  VARIABLE-TYPE = SPACE1-1
                     VARIABLE-LIST = (6)  ..

SREP-SYS1-2  =  REPORT-BLOCK  VARIABLE-TYPE = SPACE1-2
                     VARIABLE-LIST = (6)  ..

SREP-SYS1-3  =  REPORT-BLOCK  VARIABLE-TYPE = SPACE1-3
                     VARIABLE-LIST = (6)  ..

SREP-SYS2-1  =  REPORT-BLOCK  VARIABLE-TYPE = SPACE2-1
                     VARIABLE-LIST = (6,33)  ..

SREP-SYS2-2  =  REPORT-BLOCK  VARIABLE-TYPE = SPACE2-2
                     VARIABLE-LIST = (6,33)  ..

SREP-SYS2-3  =  REPORT-BLOCK  VARIABLE-TYPE = SPACE2-3
                     VARIABLE-LIST = (6)  ..

SREP-SYS2-4  =  REPORT-BLOCK  VARIABLE-TYPE = SPACE2-4
                     VARIABLE-LIST = (6)  ..

$SREP-SYS-PLM =  REPORT-BLOCK  VARIABLE-TYPE = SPACE-PLENUM
$                     VARIABLE-LIST = (6)  ..

SREP-SYS-ATC =  REPORT-BLOCK  VARIABLE-TYPE = SPACE-ATTIC
                     VARIABLE-LIST = (6)  ..

SREP-SYS-ATC-2 =  REPORT-BLOCK  VARIABLE-TYPE = SPACE-ATTIC-2
                     VARIABLE-LIST = (6)  ..

SPLANT       =  REPORT-BLOCK  VARIABLE-TYPE = PLANT1
                     VARIABLE-LIST = (3)  .. $ ZONE ELECTRICITY USE


SYSTEM-REPORT-1 = HOURLY-REPORT   REPORT-SCHEDULE = HR-SCH-SYS
    REPORT-BLOCK    =  (SREP-SYS1-1, SREP-SYS1-2, SREP-SYS1-3,
SREP-SYS2-1,SREP-SYS2-2, SREP-SYS2-3, SREP-SYS2-4, SREP-SYS-ATC,
SREP-SYS-ATC-2)  ..


END  ..
COMPUTE SYSTEMS  ..


$*************************  P  L  A  N  T  *********************
INPUT PLANT  ..
PLANT-REPORT  VERIFICATION  =  (PV-A)
              SUMMARY       =  (BEPS, BEPU, PS-D, PS-E)  ..
PLANT-PARAMETERS
    HERM-REC-COND-TYPE  =  AIR  ..

                        $ AIR-CONDITIONING SYSTEMS

A/C  =  PLANT-EQUIPMENT
    TYPE  =  HERM-REC-CHLR
    SIZE  =  -999  ..      $BASE ON PEAK LOAD



END  ..
COMPUTE PLANT  ..
STOP   ..
```

D.2 Input Files of Energy Efficiency Strategy

D.2.1 Strategy 1: Improve the Roof's Insulation

D.2.1.1 Existing Roof Construction

```
CEMENT-CPAC  =  MATERIAL
                THICKNESS     = 0.0833
                CONDUCTIVITY  = 0.4167
                DENSITY       = 116
                Specific-Heat = 0.2
                Resistance    = 0.2  ..

ROOF1  = LAYERS   MATERIAL = (CEMENT-CPAC,AL33)  ..

CEMENT-ROOF1  = CONSTRUCTION
       ABSORPTANCE = 0.88
       LAYERS = ROOF1  ..
```

D.2.1.2 Strategy 1-1: R-7 Fiberglass Insulation Underside the Roof Tiles

```
CEMENT-CPAC  =  MATERIAL
                THICKNESS     = 0.0833
                CONDUCTIVITY  = 0.4167
                DENSITY       = 116
                Specific-Heat = 0.2
                Resistance    = 0.2  ..

CRB-R7       =  MATERIAL
                THICKNESS     = 0.1667
                CONDUCTIVITY  = 0.0250
                DENSITY       = 6
                Specific-Heat = 0.2
                Resistance    = 7.12  ..

ROOF1  = LAYERS   MATERIAL = (CEMENT-CPAC,CRB-R7,AL33)  ..

CEMENT-ROOF1  = CONSTRUCTION
                ABSORPTANCE = 0.88
                LAYERS = ROOF1  ..
```

D.2.1.3 Strategy 1-2:R-14 Fiberglass Insulation Underside the Roof Tiles

```
CEMENT-CPAC  =  MATERIAL
                THICKNESS     = 0.0833
                CONDUCTIVITY  = 0.4167
                DENSITY       = 116
                Specific-Heat = 0.2
                Resistance    = 0.2  ..

CRB-R14       =  MATERIAL
                THICKNESS     = 0.3334
                CONDUCTIVITY  = 0.0250
                DENSITY       = 6
                Specific-Heat = 0.2
                Resistance    = 14.24  ..

ROOF1  = LAYERS   MATERIAL = (CEMENT-CPAC,CRB-R14,AL33)  ..

CEMENT-ROOF1  = CONSTRUCTION
                ABSORPTANCE = 0.88
```

```
                        LAYERS = ROOF1  ..
```

D.2.2 Strategy 2: Improve the 2nd Floor Ceiling Insulation

D.2.2.1 Existing 2nd Floor Ceiling Insulation

```
GYPSUM-CEILING2   =  LAYERS
        MATERIAL   = (IN02, GP01)
        THICKNESS   = (0.2957, 0.0417)  ..
GYPSUM-CEILING-2ND  =  CONSTRUCTION LAYERS = GYPSUM-CEILING2  ..
```

D.2.2.2 New 2nd Floor Ceiling Insulation

```
CRB-R28       =  MATERIAL
                THICKNESS     = 0.667
                CONDUCTIVITY  = 0.0250
                DENSITY       = 6
                Specific-Heat = 0.2
                Resistance    = 28.48  ..

GYPSUM-CEILING2   =  LAYERS
        MATERIAL   = (CRB-R28, GP01)
        THICKNESS   = (0.667, 0.0417)  ..
GYPSUM-CEILING-2ND  =  CONSTRUCTION LAYERS = GYPSUM-CEILING2  ..
```

D.2.3 Strategy 3: Improve Wall Insulation

D.2.3.1 Existing Wall Construction

```
PLASTER-MAT   =   MATERIAL
                     THICKNESS     = 0.0328
                     CONDUCTIVITY  = 0.3079
                     DENSITY       = 116
                     Specific-Heat = 0.2  ..
                   $ Resistance    = ---

BRICK-LA      =   LAYERS     MATERIAL =  (PLASTER-MAT, BK01, PLASTER-MAT)  ..
BRICK-WALL    =   CONSTRUCTION LAYERS =  BRICK-LA  ..
```

D.2.3.2 Strategy 3-1: 4” Light-weight Concrete Block

```
PLASTER-MAT   =   MATERIAL
                     THICKNESS     = 0.0328
                     CONDUCTIVITY  = 0.3079
                     DENSITY       = 116
                     Specific-Heat = 0.2  ..
                   $ Resistance    = ---

L-W-CON       =  MATERIAL
                     THICKNESS     = 0.33  $4" Concrete Block
                     CONDUCTIVITY  = 0.056
                     DENSITY       = 31
                     Specific-Heat = 0.2
                     Resistance    = 4.356  ..
```

```
BRICK-LA      =   LAYERS     MATERIAL =  (PLASTER-MAT, L-W-CON, PLASTER-MAT)  ..
BRICK-WALL    =   CONSTRUCTION LAYERS =  BRICK-LA  ..
```

D.2.3.3 Strategy 3-2: 6” Light-weight Concrete Block

```
PLASTER-MAT   =   MATERIAL
                     THICKNESS     = 0.0328
                     CONDUCTIVITY  = 0.3079
                     DENSITY       = 116
                     Specific-Heat = 0.2  ..
                   $ Resistance    = ---

L-W-CON       =  MATERIAL
                     THICKNESS     = 0.5  $ 6" Concrete Block
                     CONDUCTIVITY  = 0.056
                     DENSITY       = 31
                     Specific-Heat = 0.2
                     Resistance    = 6.534  ..


BRICK-LA      =   LAYERS     MATERIAL =  (PLASTER-MAT, L-W-CON, PLASTER-MAT)  ..
BRICK-WALL    =   CONSTRUCTION LAYERS =  BRICK-LA  ..
```

D.2.3.4 Strategy 3-3: 4” Light-weight Concrete Block with Exterior Insulation

```
PLASTER-MAT   =   MATERIAL
                     THICKNESS     = 0.0328
                     CONDUCTIVITY  = 0.3079
                     DENSITY       = 116
                     Specific-Heat = 0.2  ..
                   $ Resistance    = ---

L-W-CON       =  MATERIAL
                     THICKNESS     = 0.33  $4" Concrete Block
                     CONDUCTIVITY  = 0.056
                     DENSITY       = 31
                     Specific-Heat = 0.2
                     Resistance    = 4.356  ..

$ FOAM BOARD (EXTRUDED EXPANED POLYSTYRENE (XEPS))
F-BOARD       =  MATERIAL
                     THICKNESS     = 0.166  $2" FOAM BOARD
                     CONDUCTIVITY  = 0.033
                     DENSITY       = 1.8
                     Specific-Heat = 0.29
                     Resistance    = 10  ..

$ FIBRE CEMENT BOARD (NON-ASBESTOS FIBRE CEMENT)
F-C-B         =  MATERIAL
                     THICKNESS     = 0.0328  $ 0.394" FIBRE CEMENT BOARD
                     CONDUCTIVITY  = 0.011
                     DENSITY       = 106
                     Specific-Heat = 0.24
                     Resistance    = 0.0984  ..


BRICK-LA      =   LAYERS   MATERIAL =(F-C-B, F-BOARD, L-W-CON, PLASTER-MAT)  ..
BRICK-WALL    =   CONSTRUCTION LAYERS =  BRICK-LA  ..
```

D.2.3.4 Strategy 3-3: 4” Light-weight Concrete Block with Interior Insulation

```
PLASTER-MAT   =   MATERIAL
                     THICKNESS     = 0.0328
                     CONDUCTIVITY  = 0.3079
                     DENSITY       = 116
                     Specific-Heat = 0.2  ..
                   $ Resistance    = ---
```

```
L-W-CON       =  MATERIAL
                     THICKNESS     = 0.33  $4" Concrete Block
                     CONDUCTIVITY  = 0.056
                     DENSITY       = 31
                     Specific-Heat = 0.2
                     Resistance    = 4.356  ..

$ FOAM BOARD (EXTRUDED EXPANED POLYSTYRENE (XEPS))
F-BOARD       =  MATERIAL
                     THICKNESS     = 0.166  $2" FOAM BOARD
                     CONDUCTIVITY  = 0.033
                     DENSITY       = 1.8
                     Specific-Heat = 0.29
                     Resistance    = 10  ..

$GP01 IS 1/2 INCH GYPSUM OR PLASTER BOARD

BRICK-LA      =   LAYERS   MATERIAL =(PLASTER-MAT, L-W-CON, F-BOARD, GP01)  ..
BRICK-WALL    =   CONSTRUCTION LAYERS =  BRICK-LA  ..
```

D.2.4 Strategy 4: Low-E Window

The window properties of existing window and new window were verified by Window 4 program. The following sections show results of DOE-2 verification reports and the output from WINDOW 4 of the existing window and new window.

D.2.4.1 Existing Window: Single Pane Clear Glass

1) DOE-2 Verification Report

```
* 258 * GLASS-1  = GLASS-TYPE  GLASS-TYPE-CODE         = 1000   $ 3 mm CLEAR GLASS
* 259 *                             FRAME-ABS         = 0.7
* 260 *                             FRAME-CONDUCTANCE = 0.434  .. $

        GLAZING SELECTED FROM WINDOW LIBRARY--
        TYPE: SINGLE CLEAR

         G-T-C  LAYERS  U-SI  U-IP    SC  SHCG  TSOL  TVIS  GAP(mm)  GAS-FILL
         1000     1     6.31  1.11   1.00 0.86  0.84  0.90  0.0
```

2) WINDOW 4 Glass Property Report

```
WINDOW 4.1  DOE-2 Data File : Multi Band Calculation

Unit System : SI
Name        : DOE-2 WINDOW LIB
Desc        : Single Clear
Window ID   : 1000
Tilt        : 90.0
Glazings    : 1
Frame       :  0 None                 0.000
Spacer      :  0                      0.000   0.000   0.000
Total Height: 1097.3 mm
Total Width :  899.2 mm
Glass Height: 1097.3 mm
Glass Width :  899.2 mm
```

```
Mullion     : None
Gap        Thick   Cond  dCond    Vis   dVis   Dens   dDens     Pr     dPr
1              0       0      0      0      0      0       0      0       0
2              0       0      0      0      0      0       0      0       0
3              0       0      0      0      0      0       0      0       0
4              0       0      0      0      0      0       0      0       0
5              0       0      0      0      0      0       0      0       0
Angle     0    10    20    30    40    50    60    70    80    90 Hemis
Tsol  0.837 0.836 0.835 0.830 0.821 0.800 0.752 0.639 0.390 0.000 0.756
Abs1  0.088 0.089 0.090 0.093 0.097 0.101 0.105 0.108 0.105 0.000 0.098
Abs2      0     0     0     0     0     0     0     0     0     0     0
Abs3      0     0     0     0     0     0     0     0     0     0     0
Abs4      0     0     0     0     0     0     0     0     0     0     0
Abs5      0     0     0     0     0     0     0     0     0     0     0
Abs6      0     0     0     0     0     0     0     0     0     0     0
Rfsol 0.075 0.075 0.075 0.077 0.083 0.099 0.143 0.253 0.505 1.000 0.136
Rbsol 0.075 0.075 0.075 0.077 0.083 0.099 0.143 0.253 0.505 1.000 0.136
Tvis  0.898 0.898 0.897 0.895 0.887 0.868 0.820 0.703 0.439 0.000 0.820
Rfvis 0.081 0.081 0.081 0.083 0.090 0.107 0.154 0.270 0.534 1.000 0.146
Rbvis 0.081 0.081 0.081 0.083 0.090 0.107 0.154 0.270 0.534 1.000 0.146
SHGC  0.860 0.860 0.858 0.855 0.846 0.826 0.779 0.668 0.418 0.000 0.782
SC: 1.00


Layer ID#            2        0        0        0        0        0
Tir              0.000        0        0        0        0        0
Emis F           0.840        0        0        0        0        0
Emis B           0.840        0        0        0        0        0
Thickness(mm)      3.0        0        0        0        0        0
Cond(W/m2-C     )300.0        0        0        0        0        0
Spectral File     None     None     None     None     None     None

Overall and Center of Glass Ig U-values (W/m2-C)
Outdoor Temperature                 -17.8 C      15.6 C      26.7 C      37.8 C
Solar      WdSpd  hcout hrout  hin
(W/m2)     (m/s)     (W/m2-C)
   0        0.00  12.25  3.43  8.23  5.30 5.30  4.98 4.98  4.97 4.97  5.57 5.57
   0        6.71  25.47  3.34  8.30  6.31 6.31  5.77 5.77  5.72 5.72  6.51 6.51
 783        0.00  12.25  3.48  8.17  5.28 5.28  4.67 4.67  5.25 5.25  5.69 5.69
 783        6.71  25.47  3.37  8.27  6.29 6.29  5.59 5.59  5.97 5.97  6.61 6.61
```

2.2.1.2 New Window: Double Pane Low-E Window

1) DOE-2 Verification Report

```
* 258 * GLASS-1  = GLASS-TYPE  GLASS-TYPE-CODE         = 2638   $ Low-E Window
* 259 *                              SPACER-TYPE-CODE  = 4
* 260 *                              FRAME-ABS         = 0.2    $ White gross painted
* 261 *                              FRAME-CONDUCTANCE = 1.245  .. $ Thermally broken

        GLAZING SELECTED FROM WINDOW LIBRARY--
        TYPE: DOUBLE LOW-E (e2=.1) TINT IG

        G-T-C  LAYERS  U-SI  U-IP    SC  SHCG  TSOL  TVIS  GAP(mm)  GAS-FILL
         2638       2  1.46  0.26  0.43  0.37  0.28  0.44     12.7  Argon
```

2) WINDOW 4 Glass Property Report

```
WINDOW 4.1  DOE-2 Data File : Multi Band Calculation
Unit System : SI
Name        : DOE-2 WINDOW LIB
Desc        : Double Low-E
Window ID   : 2638
Tilt        : 90.0
Glazings    : 2
```

```
Frame       :  0 None                  0.000
Spacer      :  0 Class1                2.330  -0.010   0.138
Total Height: 1097.3 mm
Total Width :  899.2 mm
Glass Height: 1097.3 mm
Glass Width :  899.2 mm
Mullion     : None
Gap        Thick   Cond  dCond    Vis   dVis   Dens   dDens     Pr     dPr
1 Argon     12.7 0.01620  5.000  2.110  6.300  1.780 -0.0060  0.680 0.00066
2              0       0      0      0      0      0       0      0       0
3              0       0      0      0      0      0       0      0       0
4              0       0      0      0      0      0       0      0       0
5              0       0      0      0      0      0       0      0       0
Angle     0    10    20    30    40    50    60    70    80    90 Hemis
Tsol  0.283 0.284 0.280 0.273 0.265 0.249 0.216 0.156 0.069 0.000 0.232
Abs1  0.558 0.564 0.570 0.573 0.570 0.566 0.565 0.542 0.412 0.001 0.550
Abs2  0.056 0.057 0.057 0.058 0.059 0.060 0.057 0.050 0.035 0.000 0.055
Abs3      0     0     0     0     0     0     0     0     0     0     0
Abs4      0     0     0     0     0     0     0     0     0     0     0
Abs5      0     0     0     0     0     0     0     0     0     0     0
Abs6      0     0     0     0     0     0     0     0     0     0     0
Rfsol 0.102 0.095 0.093 0.096 0.107 0.125 0.161 0.252 0.484 0.999 0.152
Rbsol 0.193 0.188 0.187 0.188 0.196 0.213 0.255 0.356 0.567 1.000 0.243
Tvis  0.442 0.445 0.439 0.430 0.419 0.396 0.346 0.251 0.116 0.000 0.368
Rfvis 0.055 0.047 0.045 0.048 0.060 0.081 0.121 0.221 0.465 0.999 0.110
Rbvis 0.122 0.116 0.115 0.119 0.133 0.162 0.224 0.367 0.631 1.000 0.201
SHGC  0.367 0.369 0.365 0.359 0.351 0.336 0.301 0.233 0.125 0.000 0.314
SC: 0.43


Layer ID#          451        3        0        0        0        0
Tir              0.000    0.000        0        0        0        0
Emis F           0.840    0.840        0        0        0        0
Emis B           0.100    0.840        0        0        0        0
Thickness(mm)      6.0      6.0        0        0        0        0
Cond(W/m2-C     )150.0    150.0        0        0        0        0
Spectral File     None     None     None     None     None     None

Overall and Center of Glass Ig U-values (W/m2-C)
Outdoor Temperature                -17.8 C      15.6 C      26.7 C      37.8 C
Solar      WdSpd  hcout hrout  hin
(W/m2)     (m/s)     (W/m2-C)
   0        0.00  12.25  3.24  7.58  1.42 1.42  1.33 1.33  1.37 1.37  1.44 1.44
   0        6.71  25.47  3.21  7.60  1.49 1.49  1.38 1.38  1.42 1.42  1.49 1.49
 783        0.00  12.25  3.75  7.26  1.36 1.36  1.48 1.48  1.56 1.56  1.66 1.66
 783        6.71  25.47  3.49  6.28  1.41 1.41  1.49 1.49  1.55 1.55  1.63 1.63
```

D.2.5 Strategy 5: Shading Devices on Windows

The base-case house had no shading devices. The following is the shading devices that were installed on the base-case house.

```
WINDOW-R-1-1 =  WINDOW
                 WIDTH   = 2.293
                 HEIGHT  = 2.949
                 X = 4.593
                 Y = 2.953
                 GLASS-TYPE = GLASS-1
                 SHADING-SCHEDULE = CURTAIN-1 $ ACCOUNTED FOR THE CURTAIN
                 FRAME-WIDTH = 0.33
                 OH-W  = 2.953  OH-D  = 2.461
                 L-F-H = 3.609  L-F-D = 2.461
                 R-F-H = 3.609  R-F-D = 2.461
                 SKY-FORM-FACTOR = 0.31  ..


WINDOW-L-1-3 = WINDOW
```

```
                WIDTH   = 3.933
                HEIGHT  = 2.949
                X = 1.2155
                Y = 2.953
                 GLASS-TYPE = GLASS-1
                 FRAME-WIDTH = 0.33
                 OH-W  = 4.59   OH-D  = 2.461
                 L-F-H = 3.609  L-F-D = 2.461
                 R-F-H = 3.609  R-F-D = 2.461
                 SKY-FORM-FACTOR = 0.31  ..

WINDOW-L-1-2 = WINDOW
                WIDTH   = 3.277
                HEIGHT  = 5.902
                X = 1.9685
                Y = 10.499
                 GLASS-TYPE = GLASS-2
                 SHADING-SCHEDULE = CURTAIN-2 $ ACCOUNTED FOR THE CURTAIN
                 FRAME-WIDTH = 0.33
                 OH-W  = 3.94   OH-D  = 2.461
                 L-F-H = 6.56   L-F-D = 2.461
                 R-F-H = 6.56   R-F-D = 2.461
                 SKY-FORM-FACTOR = 0.31  ..

$ ADDITIONAL SHADING DEVICE OF WINDOW-L-1-2***************

WEST-1-2-H2   =  BUILDING-SHADE
                X=4.77  Y=27.98  Z=14.874  H=2.46  W=3.94
                AZ=270  TILT=0  ..

WEST-1-2-H3   =  BUILDING-SHADE
                X=4.77  Y=27.98  Z=12.688  H=2.46  W=3.94
                AZ=270  TILT=0  ..

$*******************************************************

WINDOW-F-2-1-1 = WINDOW
                  WIDTH   = 5.246
                  HEIGHT  = 2.949
                  X = 2.953
                  Y = 2.953
                 GLASS-TYPE = GLASS-2
                 SHADING-SCHEDULE = CURTAIN-2 $ ACCOUNTED FOR THE CURTAIN
                 FRAME-WIDTH = 0.33
                 OH-W  = 5.91   OH-D  = 2.461
                 L-F-H = 3.609  L-F-D = 2.461
                 R-F-H = 3.609  R-F-D = 2.461
                 SKY-FORM-FACTOR = 0.31  ..

WINDOW-R-2-1 = WINDOW
                WIDTH   = 2.293
                HEIGHT  = 2.949
                X = 4.593
                Y = 2.953
                 GLASS-TYPE = GLASS-2
                 SHADING-SCHEDULE = CURTAIN-2 $ ACCOUNTED FOR THE CURTAIN
                 FRAME-WIDTH = 0.33
                 OH-W  = 2.953  OH-D  = 2.461
                 L-F-H = 3.609  L-F-D = 2.461
                 R-F-H = 3.609  R-F-D = 2.461
                 SKY-FORM-FACTOR = 0.31  ..

WINDOW-L-2-1 = WINDOW
                WIDTH   = 2.293
                HEIGHT  = 2.949
                X = 3.681
                Y = 2.953
                 GLASS-TYPE = GLASS-2
                 SHADING-SCHEDULE = CURTAIN-2 $ ACCOUNTED FOR THE CURTAIN
                 FRAME-WIDTH = 0.33
                 OH-W  = 2.953  OH-D  = 2.461
                 L-F-H = 3.609  L-F-D = 2.461
                 R-F-H = 3.609  R-F-D = 2.461
                 SKY-FORM-FACTOR = 0.31  ..

WINDOW-R-2-3 = WINDOW
                WIDTH   = 2.293
```

```
                HEIGHT  = 2.949
                X = 4.101
                Y = 2.953
                 GLASS-TYPE = GLASS-2
                 SHADING-SCHEDULE = CURTAIN-2 $ ACCOUNTED FOR THE CURTAIN
                 FRAME-WIDTH = 0.33
                 OH-W  = 2.953  OH-D  = 2.461
                 L-F-H = 3.609  L-F-D = 2.461
                 R-F-H = 3.609  R-F-D = 2.461
                 SKY-FORM-FACTOR = 0.31  ..

WINDOW-L-2-3 = WINDOW
                WIDTH   = 2.289
                HEIGHT  = 2.949
                X = 4.757
                Y = 2.953
                 GLASS-TYPE = GLASS-2
                 SHADING-SCHEDULE = CURTAIN-2 $ ACCOUNTED FOR THE CURTAIN
                 FRAME-WIDTH = 0.33
                 OH-W  = 2.953  OH-D  = 2.461
                 L-F-H = 3.609  L-F-D = 2.461
                 R-F-H = 3.609  R-F-D = 2.461
                 SKY-FORM-FACTOR = 0.31  ..

$************************* ADDITIONAL SHADING DEVICES  ******************************

$ SHADING DEVICE FOR WINDOW-F-2-1-2 AND F-1-1

SOUTH-1-1-H1   =  BUILDING-SHADE
                X=21.01  Y=5.34  Z=5  H=1.64  W=8.53
                AZ=180  TILT=0  ..

SOUTH-1-1-H2   =  BUILDING-SHADE
                X=21.01  Y=5.34  Z=6  H=1.64  W=8.53
                AZ=180  TILT=0  ..

SOUTH-1-1-H3   =  BUILDING-SHADE
                X=21.01  Y=5.34  Z=7  H=1.64  W=8.53
                AZ=180  TILT=0  ..

SOUTH-1-1-H4   =  BUILDING-SHADE
                X=21.01  Y=5.34  Z=8  H=1.64  W=8.53
                AZ=180  TILT=0  ..

SOUTH-1-1-H5   =  BUILDING-SHADE
                X=21.01  Y=5.34  Z=9  H=1.64  W=8.53
                AZ=180  TILT=0  ..

SOUTH-1-1-H6   =  BUILDING-SHADE
                X=21.01  Y=5.34  Z=10  H=1.64  W=8.53
                AZ=180  TILT=0  ..

$SOUTH-1-1H7 IS NOT USED

SOUTH-1-1-H8   =  BUILDING-SHADE
                X=21.01  Y=5.34  Z=12  H=1.64  W=8.53
                AZ=180  TILT=0  ..

SOUTH-1-1-H9   =  BUILDING-SHADE
                X=21.01  Y=5.34  Z=13  H=1.64  W=8.53
                AZ=180  TILT=0  ..

SOUTH-1-1-H10   =  BUILDING-SHADE
                X=21.01  Y=5.34  Z=14  H=1.64  W=8.53
                AZ=180  TILT=0  ..

SOUTH-1-1-H11   =  BUILDING-SHADE
                X=21.01  Y=5.34  Z=15  H=1.64  W=8.53
                AZ=180  TILT=0  ..

SOUTH-1-1-H12   =  BUILDING-SHADE
                X=21.01  Y=5.34  Z=16  H=1.64  W=8.53
                AZ=180  TILT=0  ..

SOUTH-1-1-H13   =  BUILDING-SHADE
                X=21.01  Y=5.34  Z=17  H=1.64  W=8.53
                AZ=180  TILT=0  ..
```

```
SOUTH-1-1-H14   =  BUILDING-SHADE
                X=21.01  Y=5.34  Z=18  H=1.64  W=8.53
                AZ=180  TILT=0  ..
```

D.2.6 Strategy 6: High Thermal Mass Wall

D.2.6.1 Existing Wall Construction

```
PLASTER-MAT   =   MATERIAL
                     THICKNESS     = 0.0328
                     CONDUCTIVITY  = 0.3079
                     DENSITY       = 116
                     Specific-Heat = 0.2  ..
                  $ Resistance    = ---

BRICK-LA      =   LAYERS     MATERIAL =  (PLASTER-MAT, BK01, PLASTER-MAT)  ..
BRICK-WALL    =   CONSTRUCTION LAYERS =  BRICK-LA  ..
```

D.2.6.2 Strategy 6-1: High Thermal Mass Wall (8” Brick)

```
PLASTER-MAT   =   MATERIAL
                     THICKNESS     = 0.0328
                     CONDUCTIVITY  = 0.3079
                     DENSITY       = 116
                     Specific-Heat = 0.2  ..
                  $ Resistance    = ---

BRICK-LA      =   LAYERS     MATERIAL =  (PLASTER-MAT, BK02, PLASTER-MAT)  ..
BRICK-WALL    =   CONSTRUCTION LAYERS =  BRICK-LA  ..

$BK02 is 8 inch thick common brick
```

D.2.6.3 Strategy 6-2: High Thermal Mass Wall (12” Brick)

```
PLASTER-MAT   =   MATERIAL
                     THICKNESS     = 0.0328
                     CONDUCTIVITY  = 0.3079
                     DENSITY       = 116
                     Specific-Heat = 0.2  ..
                  $ Resistance    = ---

BRICK-LA-2    =   LAYERS     MATERIAL =  (PLASTER-MAT, BK01, PLASTER-MAT)  ..
BRICK-WALL-2  =   CONSTRUCTION LAYERS =  BRICK-LA-2  ..

BRICK-LA      =   LAYERS     MATERIAL =  (PLASTER-MAT, BK03, PLASTER-MAT)  ..
BRICK-WALL    =   CONSTRUCTION LAYERS =  BRICK-LA  ..

$BK03 is 12 inch thick common brick
```

D.2.7 Strategy 7: High Energy Efficient Air-Conditioning Systems

D.2.7.1 Existing Air-Conditioning Systems

```
$ SYSTEMS

    $SYSTEM FOR SPACE2-1
       SYS2-1 = SYSTEM
                SYSTEM-TYPE       =  RESYS
```

```
                ZONE-NAMES        =  (SPACE2-1)
                MAX-SUPPLY-T      =  77.05
                MIN-SUPPLY-T      =  70.0
              HEATING-SCHEDULE    =  YEAR-SHUT   $ NO HEATING
                HEATING-CAPACITY  =  0           $ NO HEATING
                HEAT-SOURCE       =  ELECTRIC    $ NO HEATING
              COOLING-SCHEDULE    =  COOL2-1YEAR
                COOLING-CAPACITY  =  17401
                COOLING-EIR       =  0.325  ..

$ NOTE***********************************************
$ DATA FROM THE AIR-CONDTIONING SYSTEM'S MANUFACTURE
$ BRAND: DAIKIN, MODEL: FT18GV1LS
$ SEER = 10.5
$ COOLING-EIR = 3.41/SEER = 3.412/10.5 = 0.325
$ NOTE***********************************************


     $SYSTEM FOR SPACE2-2
        SYS2-2 = SYSTEM
                SYSTEM-TYPE       =  RESYS
                ZONE-NAMES        =  (SPACE2-2)
                MAX-SUPPLY-T      =  77.05
                MIN-SUPPLY-T      =  70.0
              HEATING-SCHEDULE    =  YEAR-SHUT   $ NO HEATING
                HEATING-CAPACITY  =  0           $ NO HEATING
                HEAT-SOURCE       =  ELECTRIC    $ NO HEATING
              COOLING-SCHEDULE    =  COOL2-2YEAR
                COOLING-CAPACITY  =  12000
                COOLING-EIR       =  0.325   ..

$ NOTE***********************************************
$ DATA FROM THE AIR-CONDTIONING SYSTEM'S MANUFACTURE
$ BRAND: CARRIER, MODEL: 42RS012
$ SEER = 10.5
$ COOLING-EIR = 3.41/SEER = 3.41/10.5 = 0.325
$ NOTE***********************************************
```

D.2.7.1 Proposed Air-Conditioning Systems

```
$ SYSTEMS

    $SYSTEM FOR SPACE2-1
       SYS2-1 = SYSTEM
                SYSTEM-TYPE       =  RESYS
                ZONE-NAMES        =  (SPACE2-1)
                MAX-SUPPLY-T      =  77.05
                MIN-SUPPLY-T      =  70.0
              HEATING-SCHEDULE    =  YEAR-SHUT   $ NO HEATING
                HEATING-CAPACITY  =  0           $ NO HEATING
                HEAT-SOURCE       =  ELECTRIC    $ NO HEATING
              COOLING-SCHEDULE    =  COOL2-1YEAR
                COOLING-CAPACITY  =  17401
                COOLING-EIR       =  0.284  ..

$ NOTE*******************************************************
$ Proposed New A/C has EER of 12, COP of 12/3.412 = 3.517
$ COOLING-EIR = 1/COP
$             = 1/3.517 = 0.284
$ NOTE*******************************************************

    $SYSTEM FOR SPACE2-2
       SYS2-2 = SYSTEM
                SYSTEM-TYPE       =  RESYS
                ZONE-NAMES        =  (SPACE2-2)
                MAX-SUPPLY-T      =  77.05
                MIN-SUPPLY-T      =  70.0
              HEATING-SCHEDULE    =  YEAR-SHUT   $ NO HEATING
                HEATING-CAPACITY  =  0           $ NO HEATING
                HEAT-SOURCE       =  ELECTRIC    $ NO HEATING
              COOLING-SCHEDULE    =  COOL2-2YEAR
                COOLING-CAPACITY  =  12000
```

```
                    COOLING-EIR       =  0.284  ..

$ NOTE*******************************************************
$ Proposed New A/C has EER of 12, COP of 12/3.412 = 3.517
$ COOLING-EIR = 1/COP
$             = 1/3.517 = 0.284
$ NOTE*******************************************************
```

D.2.8 Strategy 8: Energy Efficient Lighting – Electronic Ballasts

D.2.8.1 Existing Lighting Load

```
                        $ SPECIFIC SPACE DETAILS

$ SPACE 1-1 : LIVING ROOM, DINING AREA, KITCHEN, BATHROOM
SPACE1-1   =   SPACE
               SPACE-CONDITIONS  =  LIVING-SPACE
               PEOPLE-SCHEDULE   =  OCC1-1YEAR
               LIGHTING-SCHEDULE =  LIGHT1-1YEAR
               EQUIP-SCHEDULE    =  EQUIP1-1YEAR
               LIGHTING-KW       =  0.0992
               EQUIPMENT-KW      =  2.3      $ was 2.495
               INF-SCHEDULE      =  INFIL-YEAR-L
               INF-METHOD        =  AIR-CHANGE
               AIR-CHANGES/HR    =  10            $ INDIVIDUAL
               AREA              =  757.44   $ Nominal value- 60% larger than the actual
(473.40)
               VOLUME            =  2329.7  .. $ Nominal value- 60% less than tha actual
(3882.87)
```

D.2.8.2 Improved Lighting Load

```
                        $ SPECIFIC SPACE DETAILS

$ SPACE 1-1 : LIVING ROOM, DINING AREA, KITCHEN, BATHROOM
SPACE1-1   =   SPACE
               SPACE-CONDITIONS  =  LIVING-SPACE
               PEOPLE-SCHEDULE   =  OCC1-1YEAR
               LIGHTING-SCHEDULE =  LIGHT1-1YEAR
               EQUIP-SCHEDULE    =  EQUIP1-1YEAR
               LIGHTING-KW       =  0.084   $ a 15% reduction from 0.0992 KW
               EQUIPMENT-KW      =  2.3      $ Nominal value (was 2.495)
               INF-SCHEDULE      =  INFIL-YEAR-L
               INF-METHOD        =  AIR-CHANGE
               AIR-CHANGES/HR    =  10            $ INDIVIDUAL
               AREA              =  757.44   $ Nominal value- 60% larger than the actual
(473.40)
               VOLUME            =  2329.7  .. $ Nominal value- 60% less than tha actual
(3882.87)
```

D.2.9 Strategy 9: Energy Efficient Refrigerators

D.2.9.1 Existing Refrigerator Loads

```
                              $ EQUIPMENT SCHEDULE

$ SPACE 1-1 : LIVING ROOM (TV-85 W + Electric Fan-60 W = 145 W)
$   DINING ROOM (MICROWAVE OVEN-1000 W + TOASTER-700 W = 1700 W)
```

```
$   KITCHEN ROOM (REFRIGERATOR-150 W (657 kwh/year) + ELECTRIC RICE COOKER-700 W = 650 W)
$
$   TOTAL  = 2495 W OR 2.495 KW (Adjusted to 2.3 KW)

EQUIP1-1WD   =   DAY-SCHEDULE
                (1,7)(0.0326)  (8)(0.0519)  (9,17)(0.0326)  (18)(0.109)
                (19,20)(0.0736)  (21,24)(0.0326)  ..
EQUIP1-1WE   =   DAY-SCHEDULE
                (1,7)(0.0326)  (8)(0.0519)  (9,10)(0.0326)
                (11,17)(0.0736)  (18)(0.109) (19,20)(0.0736)
                (21,24)(0.0326)  ..
EQUIP1-1WEEK =   WEEK-SCHEDULE
                (WD) EQUIP1-1WD   (WEH) EQUIP1-1WE  ..
EQUIP1-1YEAR =   SCHEDULE
                THRU DEC 31 EQUIP1-1WEEK  ..


$ SPACE 2-4 : BATHROOM & HALL
$             (REFRIGERATOR 100 W, 427 kWh/year)
EQUIP2-4WD   =   DAY-SCHEDULE
                 (1,24)(0.486)  ..
EQUIP2-4WE   =   DAY-SCHEDULE
                 (1,24)(0.486)  ..
EQUIP2-4WEEK =   WEEK-SCHEDULE
                 (WD)EQUIP2-4WD   (WEH) EQUIP2-4WE  ..
EQUIP2-4YEAR =   SCHEDULE
                  THRU DEC 31 EQUIP2-4WEEK  ..
```

D.2.9.2 Improved Refrigerator Loads

```
                        $ EQUIPMENT SCHEDULE

$ SPACE 1-1:  LIVING ROOM
$ Refrigerator Energy Use = 372 kWh/year

EQUIP1-1WD   =   DAY-SCHEDULE
                (1,7)(0.01846)  (8)(0.037)  (9,17)(0.01846)  (18)(0.0945)
                (19,20)(0.059)  (21,24)(0.01846)  ..
EQUIP1-1WE   =   DAY-SCHEDULE
                (1,7)(0.01846)  (8)(0.037)  (9,10)(0.01846)
                (11,17)(0.059)  (18)(0.0958) (19,20)(0.0595)
                (21,24)(0.01846)  ..
EQUIP1-1WEEK =   WEEK-SCHEDULE
                (WD) EQUIP1-1WD   (WEH) EQUIP1-1WE  ..
EQUIP1-1YEAR =   SCHEDULE
                THRU DEC 31 EQUIP1-1WEEK  ..



$ SPACE 2-4 : BATHROOM & HALL
$ Refrigerator Energy Use = 316 kWh/year

EQUIP2-4WD   =   DAY-SCHEDULE
                 (1,24)(0.3607)  ..
EQUIP2-4WE   =   DAY-SCHEDULE
                 (1,24)(0.3607)  ..
EQUIP2-4WEEK =   WEEK-SCHEDULE
                 (WD)EQUIP2-4WD   (WEH) EQUIP2-4WE  ..
EQUIP2-4YEAR =   SCHEDULE
                  THRU DEC 31 EQUIP2-4WEEK  ..
```

D.3 Results of Run# 1 and Run#16 (Base-case) Zone Temperatures

The results of the case-study house's simulated zone temperatures from Run# 1 as compared to the measured temperature are presented in Figure D.2 to D.5. The results of the

case-study house's simulated zone temperatures from Run# 16, which was considered as the base-case, as compared to the measured temperature are presented in Figure D.6 to D.9.

D.4 DOE-2 Hourly Reports

DOE-2 hourly report of indoor temperature of the base-case house, the base-case house with energy efficiency strategies, and renewable energy systems are presented in Sections D.4.1 and D.4.2. The presented hourly data is an example of one day data (September 17, 2000).

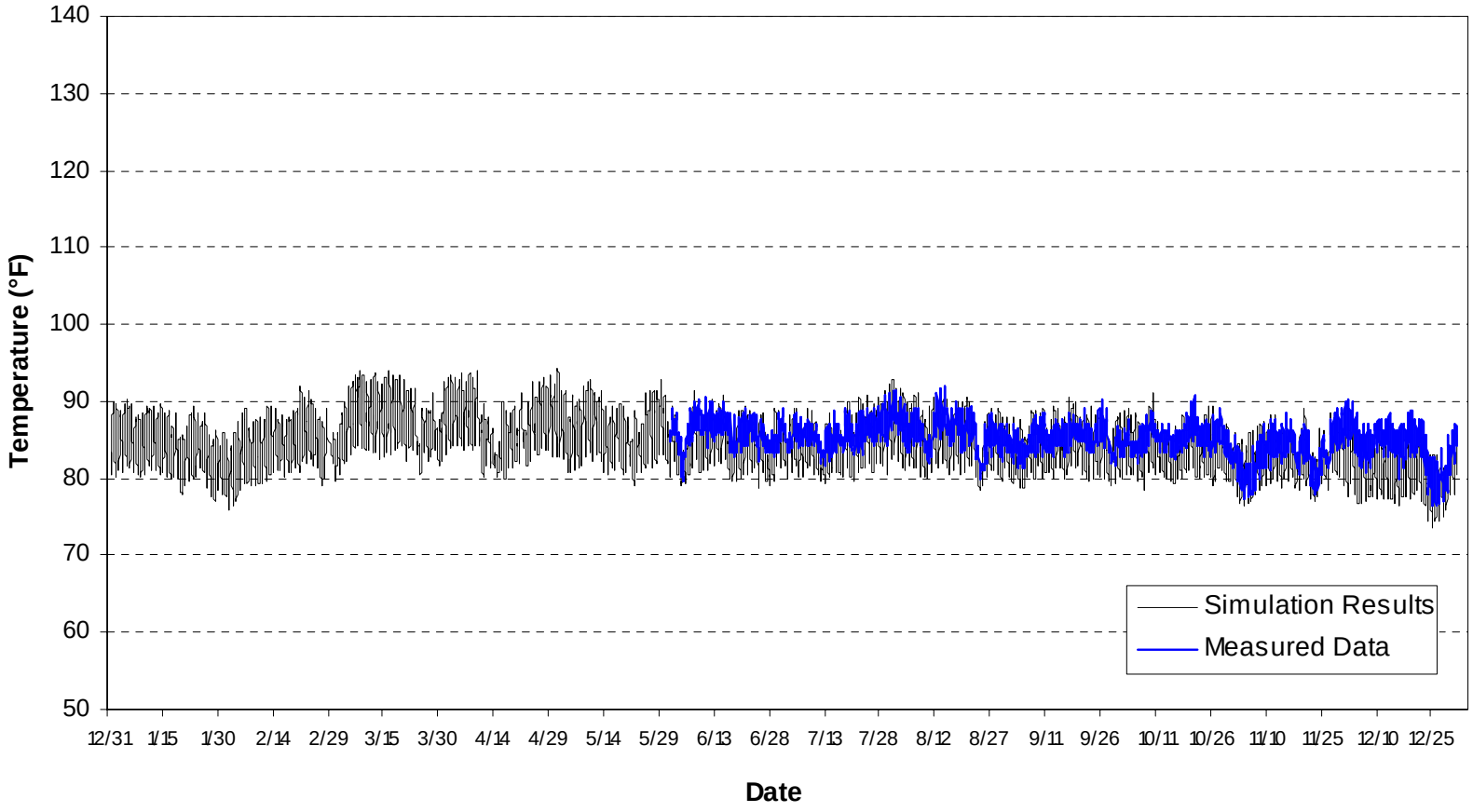


Figure D.2 *Comparison of Run# 1 Simulated and Measured Living Room Temperatures.*

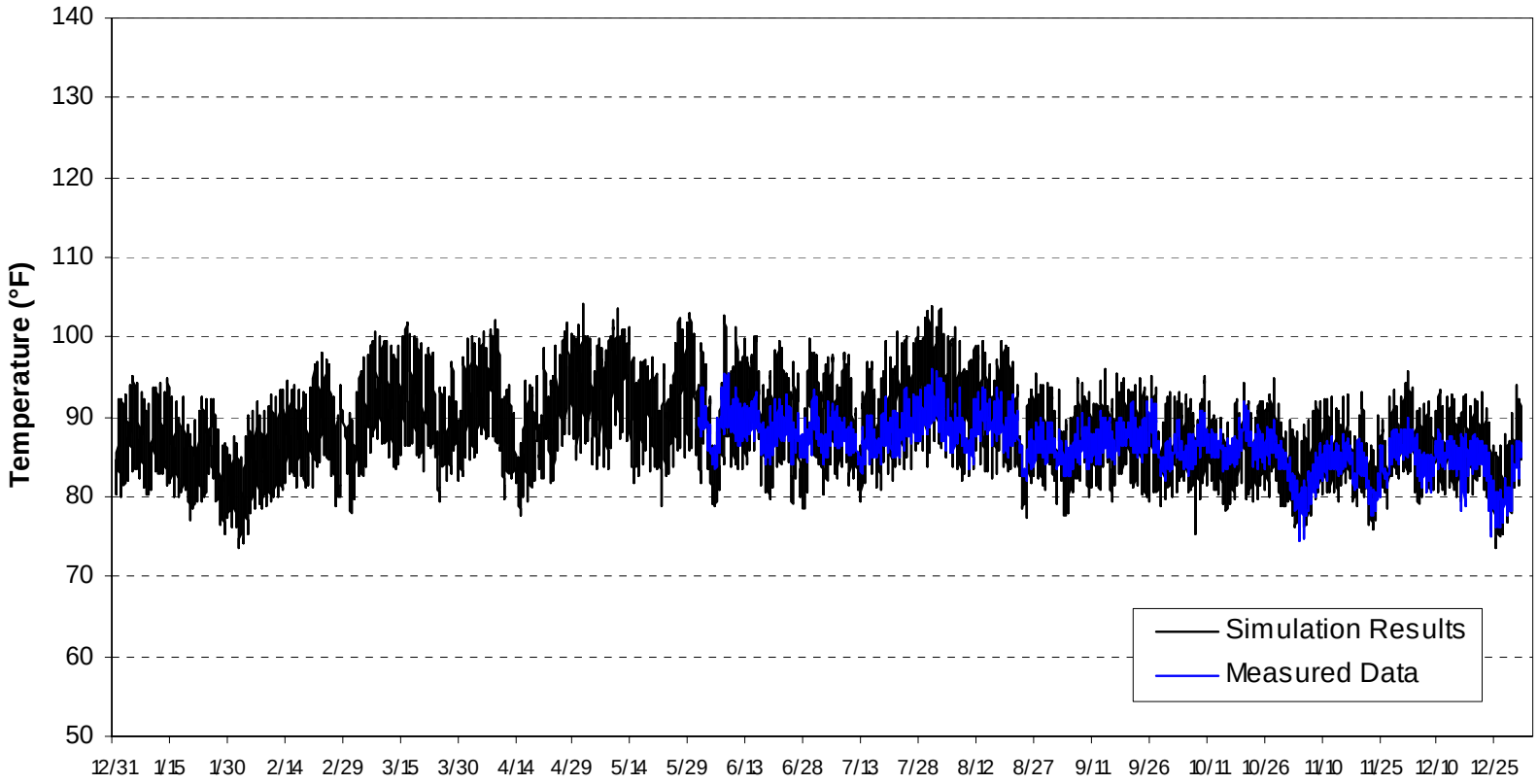


Figure D.3 *Comparison of Run# 1 Simulated and Measured Bedroom-3 Temperatures.*

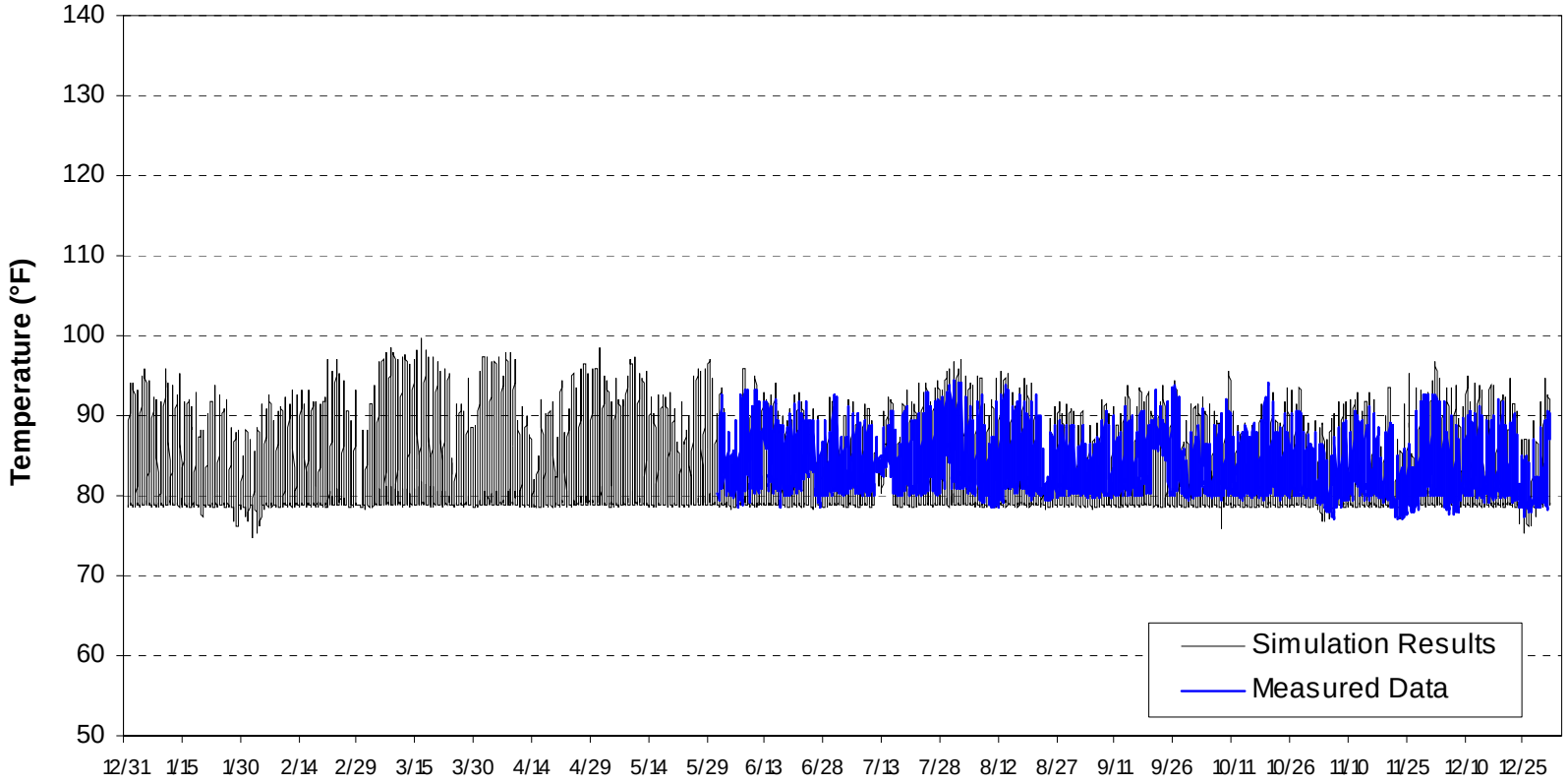


Figure D.4 ***Comparison of Run# 1 Simulated and Measured the Master Bedroom Temperatures***.

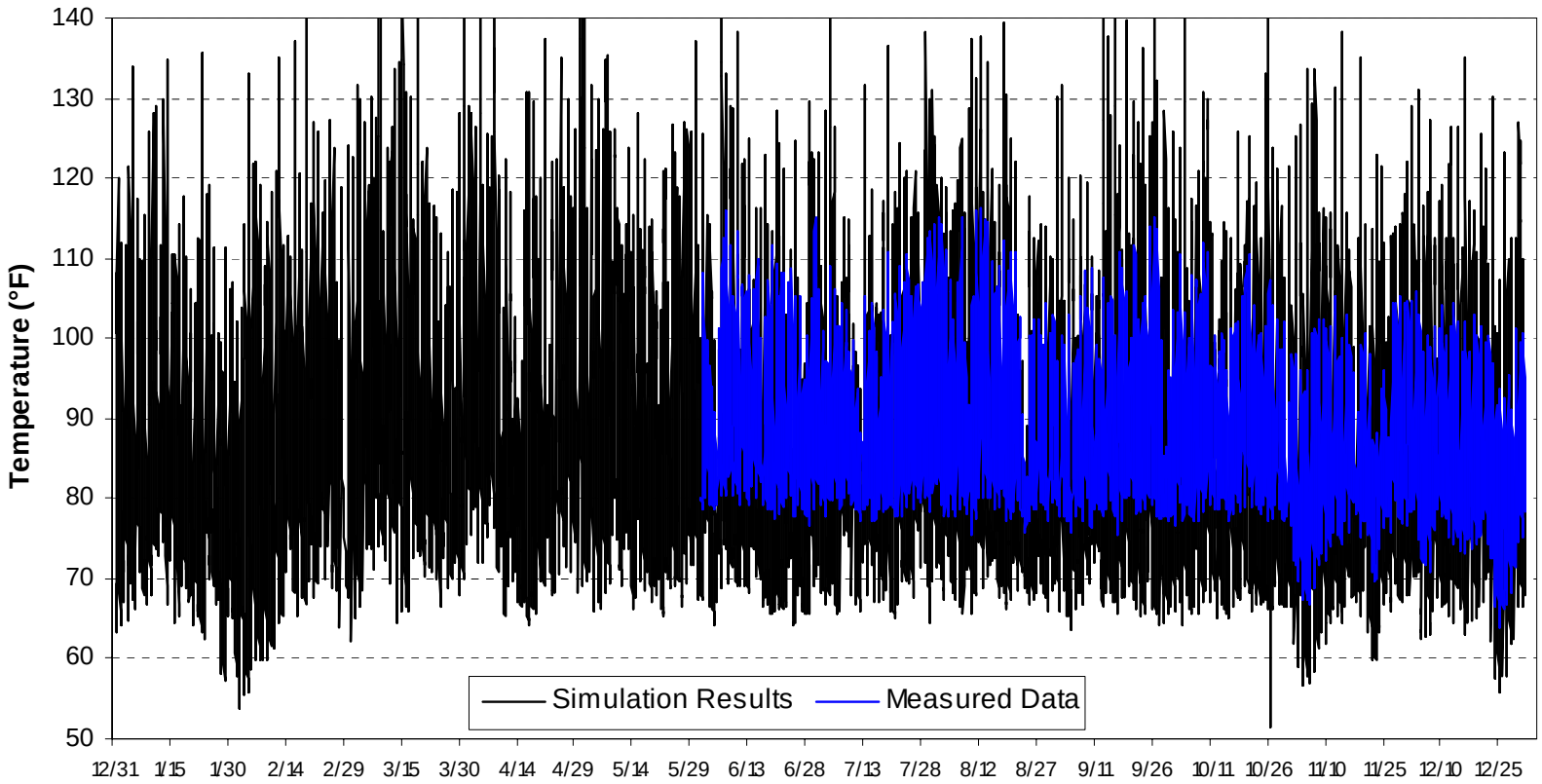


Figure D.5 *Comparison of Run# 1 Simulated and Measured Attic Temperatures.*

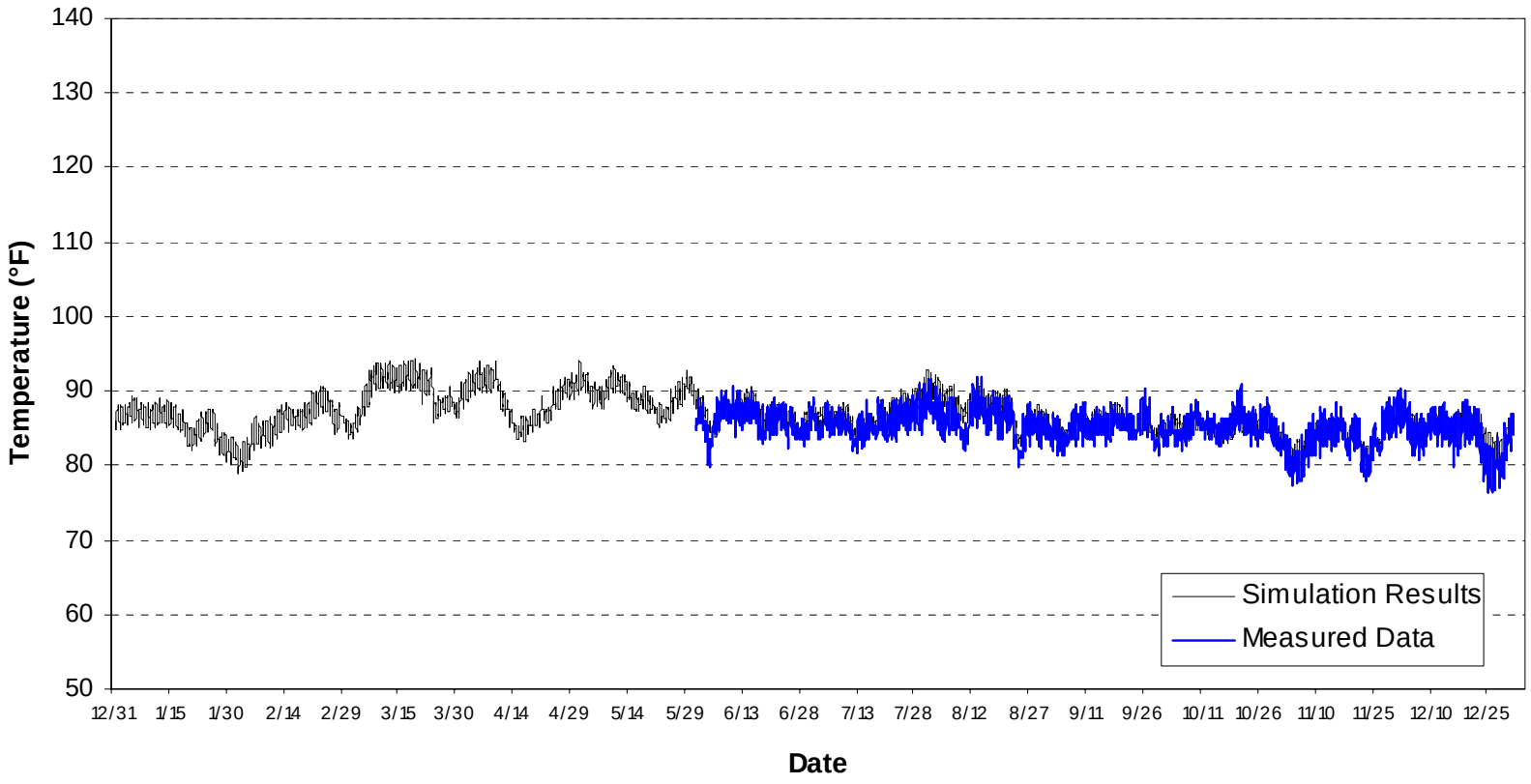


Figure D.6 *Comparison of Run# 16 Simulated and Measured Living Room Temperatures.*

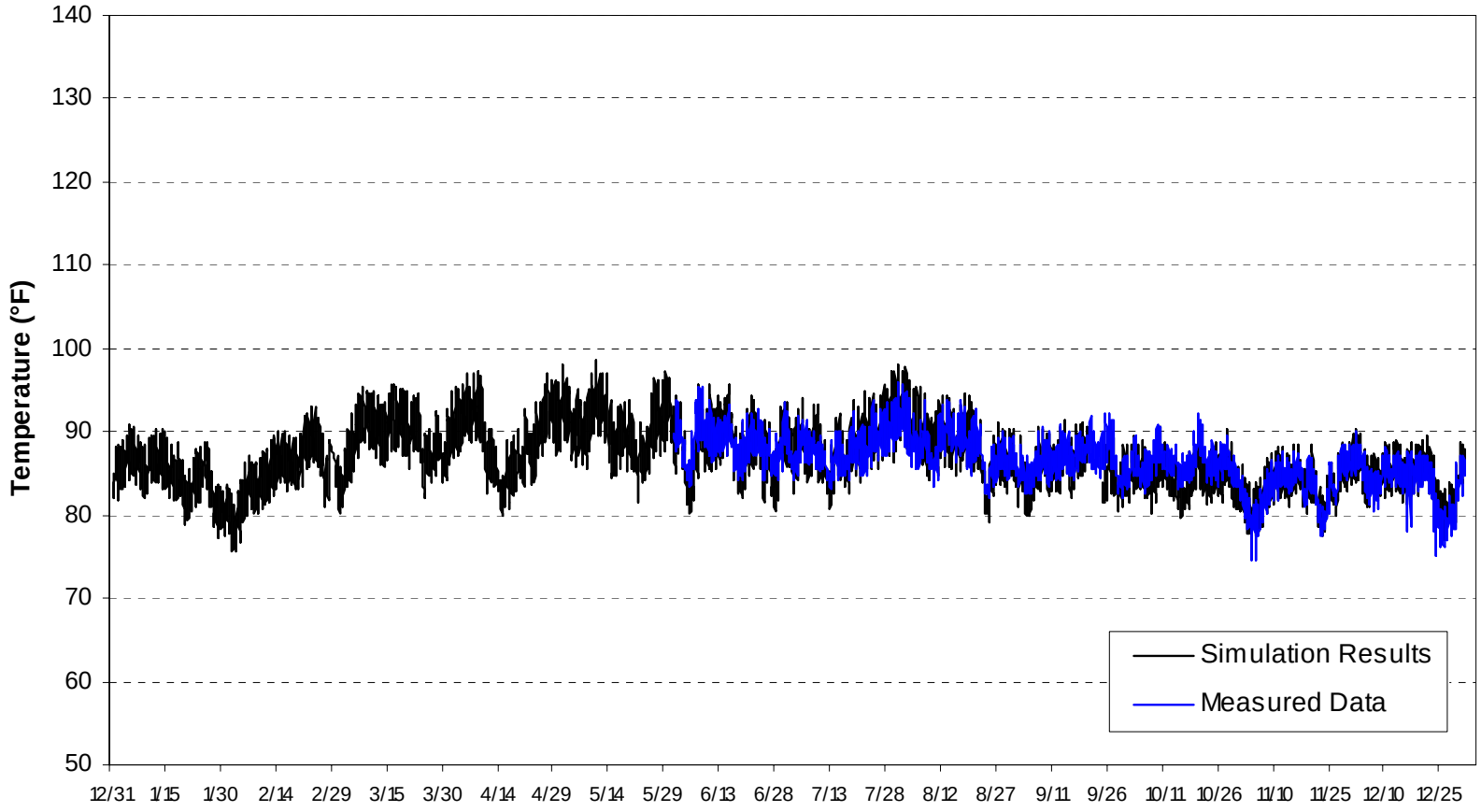


Figure D.7 *Comparison of Run# 16 Simulated and Measured Bedroom-3 Temperatures.*

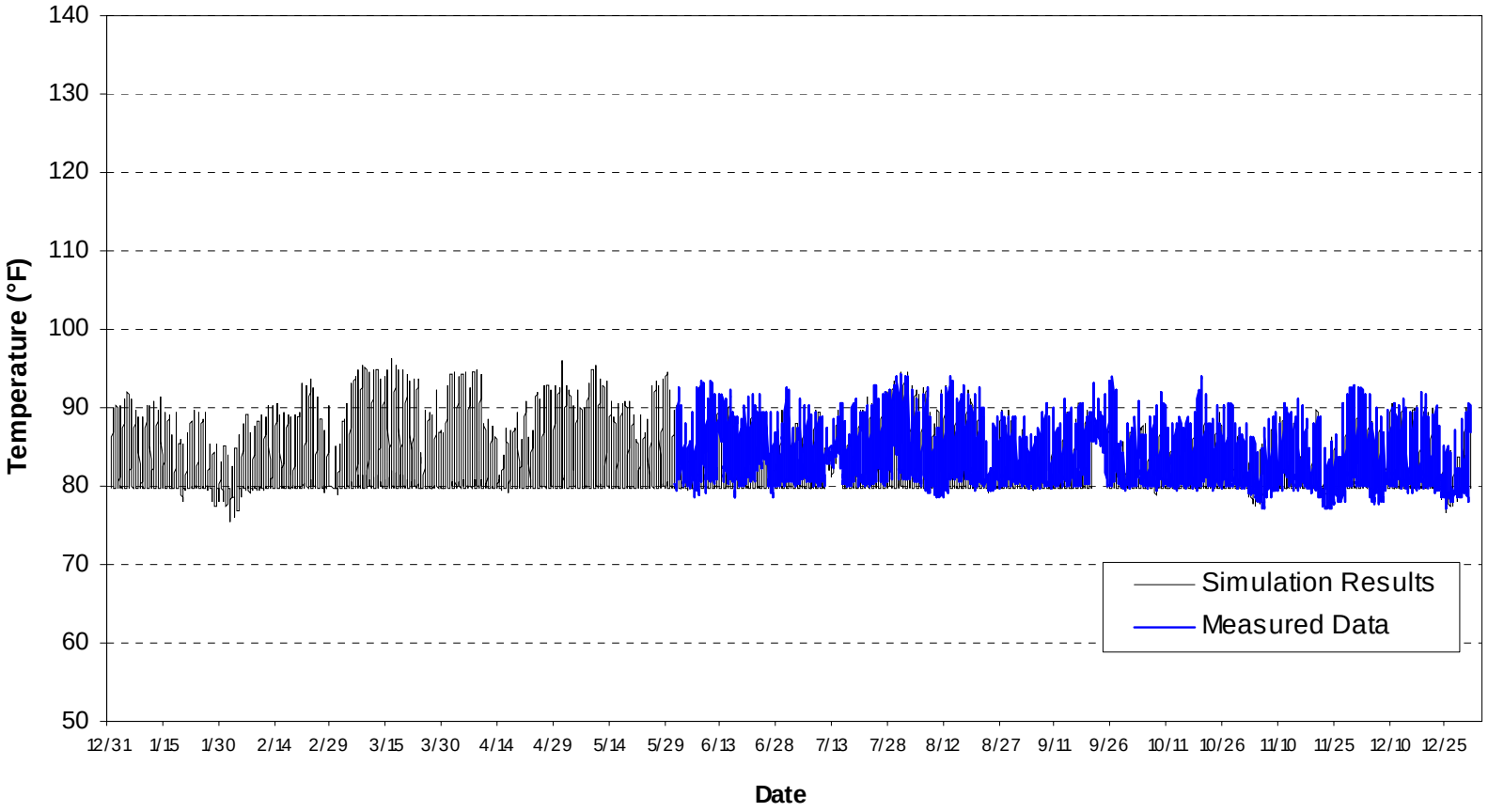


Figure D.8 *Comparison of Run# 16 Simulated and Measured Master Temperatures.*

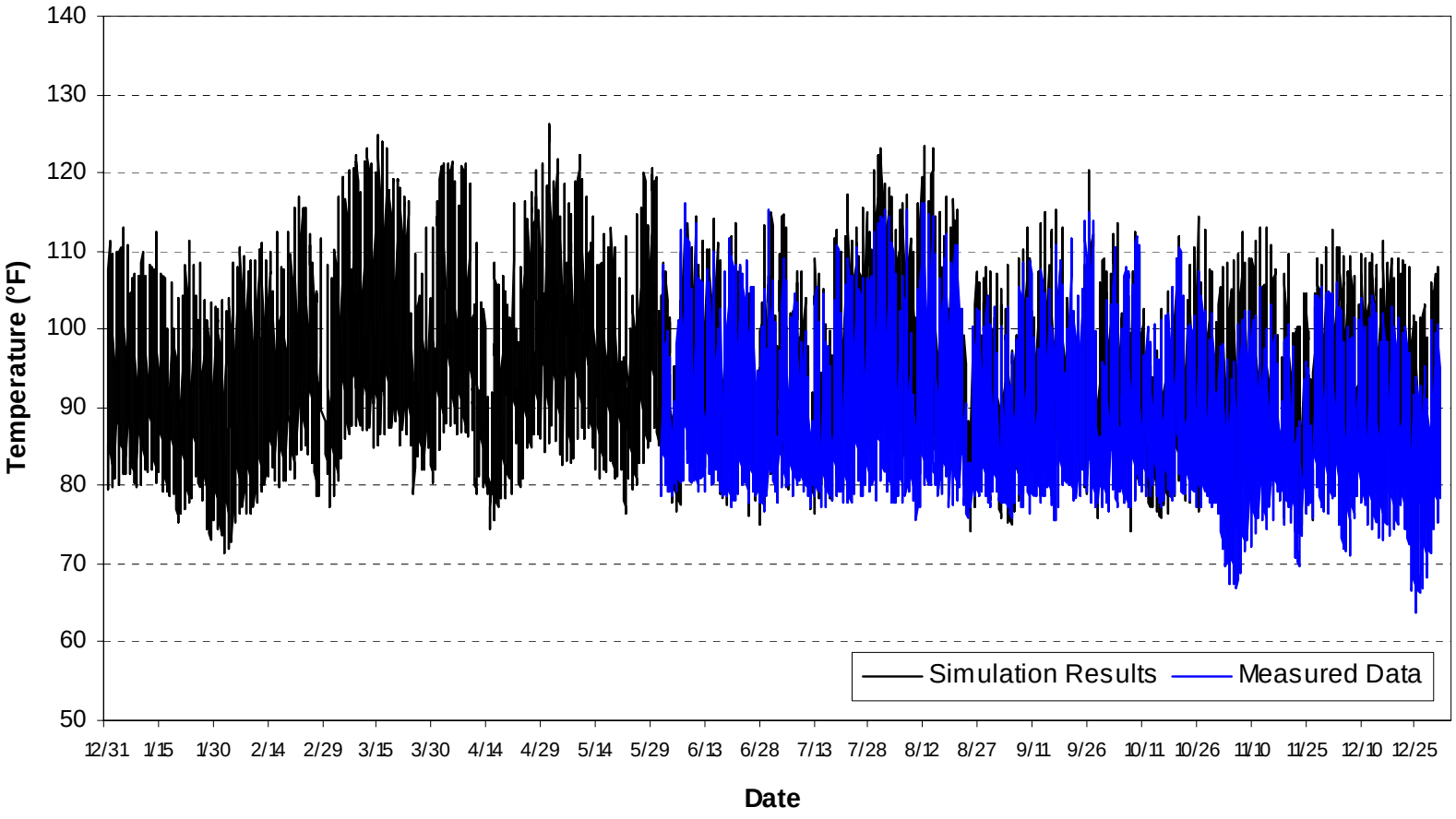


Figure D.9 *Comparison of Run# 16 Simulated and Measured Attic Temperatures.*

D.4.1 DOE-2 Hourly Report of Indoor Temperature of the Base-Case House

```
1CASE STUDY HOUSE:THE JEERASAK'S HOUSE,  Base-Case                              DOE-2.1E-119  Fri Jan 30 20:08:49 2004SDL RUN  1
 RUN DESCRIPTION:RUN# 16
 SYSTEM-REPORT-1  = HOURLY-REPORT                                                                                   PAGE260 -  1
 ---------------------------------------------------------------------------------------------------------------------------------
        SPACE1-1 SPACE1-2 SPACE1-3 SPACE2-1 SPACE2-2 SPACE2-3 SPACE2-4 SPACE-AT

        ZONE     ZONE     ZONE     ZONE     ZONE     ZONE     ZONE     ZONE
        TEMP     TEMP     TEMP     TEMP     TEMP     TEMP     TEMP     TEMP
        F        F        F        F        F        F        F        F

        ----( 6) ----( 6) ----( 6) ----( 6) ----( 6) ----( 6) ----( 6) ----( 6)
  917 1     85.4     84.3     85.7     79.7     80.5     85.6     86.6     84.1
  917 2     85.2     83.9     85.3     79.7     80.5     84.6     85.5     82.8
  917 3     85.0     83.4     85.1     79.7     80.5     84.1     85.2     81.8
  917 4     84.9     83.0     84.8     79.7     80.5     83.7     84.9     81.0
  917 5     84.7     82.6     84.7     79.6     80.4     83.2     84.7     80.0
  917 6     85.0     82.1     84.4     79.6     80.5     83.1     84.6     87.4
  917 7     85.6     82.2     84.5     79.7     80.5     83.3     84.8     95.1
  917 8     86.0     82.5     84.7     82.6     88.3     83.6     85.6    100.9
  917 9     86.3     83.3     85.3     84.2     90.7     84.8     87.5    105.4
  91710     87.0     84.2     85.9     85.8     92.5     85.7     88.6    109.6
  91711     87.6     85.0     86.4     87.1     93.5     86.6     89.5    112.9
  91712     87.8     85.9     86.8     88.4     94.3     87.4     90.1    115.2
  91713     88.1     86.8     87.2     89.4     94.8     88.3     90.6    112.7
  91714     88.3     87.6     87.5     90.3     95.1     89.1     91.0    111.1
  91715     88.3     88.2     87.7     90.6     95.1     89.6     91.3    105.4
  91716     88.2     88.5     87.9     90.7     94.8     90.9     91.3    101.0
  91717     87.9     88.5     88.1     90.5     94.4     90.1     91.3     97.8
  91718     88.1     88.4     88.2     90.4     94.0     90.0     91.2     95.7
  91719     87.8     88.4     88.2     79.9     80.6     89.7     91.3     94.0
  91720     87.6     87.7     87.1     80.0     80.7     88.4     87.8     92.6
  91721     87.3     87.2     86.9     79.9     80.6     87.9     87.4     91.0
  91722     87.1     86.8     86.7     79.9     80.6     87.5     87.1     89.9
  91723     86.8     86.4     86.6     79.8     80.6     87.1     86.9     88.9
  91724     86.7     86.1     86.4     79.8     80.5     86.6     86.6     87.8
0 DAILY SUMMARY (SEP 17)
     MN     84.7     82.1     84.4     79.6     80.4     83.1     84.6     80.0
     MX     88.3     88.5     88.2     90.7     95.1     90.9     91.3    115.2
     SM   2082.6   2053.0   2072.2   2007.0   2074.5   2080.9   2111.3   2304.2
     AV     86.8     85.5     86.3     83.6     86.4     86.7     88.0     96.0
```

D.4.2 DOE-2 Hourly Report of Indoor Temperature of the Energy Efficiency Strategies

D.3.2.1 DOE-2 Hourly Report of Indoor Temperature of the Energy Efficiency Strategy 1-1 (R-7 Insulation Underside the Roof Tiles)

```
1CASE STUDY HOUSE:THE JEERASAK'S HOUSE,  Model Improvement Strategy 1-1          DOE-2.1E-119  Mon Feb  2 00:35:15 2004SDL RUN  1
 R-7 Insulation behind the roof tiles
 SYSTEM-REPORT-1  = HOURLY-REPORT                                                                                    PAGE260 -  1
 ---------------------------------------------------------------------------------------------------------------------------------
        SPACE1-1 SPACE1-2 SPACE1-3 SPACE2-1 SPACE2-2 SPACE2-3 SPACE2-4 SPACE-AT

        ZONE     ZONE     ZONE     ZONE     ZONE     ZONE     ZONE     ZONE
        TEMP     TEMP     TEMP     TEMP     TEMP     TEMP     TEMP     TEMP
        F        F        F        F        F        F        F        F

        ----( 6) ----( 6) ----( 6) ----( 6) ----( 6) ----( 6) ----( 6) ----( 6)
  917 1     85.4     84.3     85.6     79.7     80.5     85.5     86.4     86.3
  917 2     85.2     83.9     85.2     79.7     80.5     84.5     85.4     85.7
  917 3     85.0     83.4     85.0     79.7     80.5     84.1     85.1     85.2
  917 4     84.8     83.0     84.7     79.7     80.5     83.6     84.8     84.8
  917 5     84.6     82.6     84.6     79.6     80.4     83.2     84.6     84.3
  917 6     85.0     82.1     84.4     79.6     80.5     83.1     84.5     86.4
  917 7     85.6     82.1     84.4     79.7     80.5     83.2     84.7     88.3
  917 8     86.0     82.4     84.6     82.4     88.1     83.4     85.4     90.2
  917 9     86.2     83.1     85.2     83.8     90.4     84.5     87.1     91.7
  91710     87.0     83.9     85.7     85.3     92.1     85.3     88.1     93.3
  91711     87.6     84.7     86.2     86.5     93.0     86.1     88.9     94.5
  91712     87.8     85.5     86.7     87.6     93.7     86.9     89.4     95.5
  91713     88.0     86.4     87.0     88.6     94.1     87.7     89.9     95.2
  91714     88.2     87.2     87.3     89.5     94.4     88.4     90.2     95.1
  91715     88.3     87.8     87.5     89.9     94.4     89.0     90.5     93.8
  91716     88.1     88.1     87.7     90.0     94.2     90.3     90.6     92.7
  91717     87.8     88.2     87.9     89.9     93.8     89.6     90.7     91.9
  91718     88.0     88.2     88.0     89.9     93.5     89.5     90.7     91.2
  91719     87.8     88.1     88.0     79.8     80.6     89.3     90.8     90.6
  91720     87.6     87.4     87.0     79.9     80.7     88.1     87.4     90.0
  91721     87.2     87.0     86.8     79.9     80.6     87.6     87.1     89.5
  91722     87.1     86.6     86.6     79.9     80.6     87.2     86.8     89.0
  91723     86.8     86.3     86.4     79.8     80.6     86.8     86.6     88.6
  91724     86.6     85.9     86.3     79.8     80.5     86.4     86.4     88.2
0 DAILY SUMMARY (SEP 17)
     MN     84.6     82.1     84.4     79.6     80.4     83.1     84.5     84.3
     MX     88.3     88.2     88.0     90.0     94.4     90.3     90.8     95.5
     SM   2082.0   2048.2   2068.7   2000.5   2068.6   2073.3   2102.0   2161.9
     AV     86.8     85.3     86.2     83.4     86.2     86.4     87.6     90.1
```

D.4.2.2 DOE-2 Hourly Report of Indoor Temperature of the Energy Efficiency Strategy 1-2 (R-14 Insulation Underside the Roof Tiles)

```
1CASE STUDY HOUSE:THE JEERASAK'S HOUSE,  Model Improvement Strategy 1-2          DOE-2.1E-119  Mon Feb  2 01:15:58 2004SDL RUN  1
 R-14 Insulation behind the roof tiles
 SYSTEM-REPORT-1  = HOURLY-REPORT                                                                                   PAGE260 -  1
 ---------------------------------------------------------------------------------------------------------------------------------
        SPACE1-1 SPACE1-2 SPACE1-3 SPACE2-1 SPACE2-2 SPACE2-3 SPACE2-4 SPACE-AT
        ZONE     ZONE     ZONE     ZONE     ZONE     ZONE     ZONE     ZONE
        TEMP     TEMP     TEMP     TEMP     TEMP     TEMP     TEMP     TEMP
        F        F        F        F        F        F        F        F

        ----( 6) ----( 6) ----( 6) ----( 6) ----( 6) ----( 6) ----( 6) ----( 6)
  917 1     85.4     84.2     85.6     79.7     80.5     85.4     86.3     86.1
  917 2     85.2     83.8     85.2     79.7     80.5     84.5     85.3     85.7
  917 3     85.0     83.4     84.9     79.7     80.5     84.0     85.0     85.3
  917 4     84.8     83.0     84.7     79.7     80.5     83.6     84.8     85.0
  917 5     84.6     82.6     84.5     79.6     80.4     83.2     84.6     84.6
  917 6     85.0     82.1     84.3     79.6     80.5     83.1     84.5     85.8
  917 7     85.6     82.1     84.4     79.7     80.5     83.2     84.7     86.9
  917 8     86.0     82.4     84.6     82.4     88.1     83.3     85.3     88.1
  917 9     86.2     83.1     85.2     83.8     90.3     84.4     87.0     89.1
  91710     87.0     83.9     85.7     85.2     92.0     85.2     88.0     90.1
  91711     87.5     84.7     86.2     86.4     92.9     86.0     88.7     90.9
  91712     87.8     85.4     86.6     87.5     93.6     86.7     89.3     91.6
  91713     88.0     86.3     87.0     88.5     94.0     87.5     89.7     91.5
  91714     88.2     87.1     87.3     89.3     94.2     88.3     90.1     91.6
  91715     88.3     87.7     87.5     89.7     94.2     88.8     90.3     90.9
  91716     88.1     88.0     87.7     89.9     94.0     90.2     90.5     90.4
  91717     87.8     88.2     87.8     89.8     93.7     89.4     90.5     89.9
  91718     88.0     88.1     87.9     89.8     93.3     89.4     90.5     89.5
  91719     87.8     88.0     88.0     79.8     80.6     89.2     90.6     89.2
  91720     87.6     87.4     86.9     79.9     80.7     88.0     87.3     88.8
  91721     87.2     87.0     86.7     79.9     80.6     87.5     87.0     88.4
  91722     87.1     86.5     86.5     79.9     80.6     87.1     86.8     88.1
  91723     86.8     86.2     86.4     79.8     80.6     86.7     86.5     87.8
  91724     86.6     85.9     86.2     79.8     80.5     86.4     86.3     87.5
0 DAILY SUMMARY (SEP 17)
     MN     84.6     82.1     84.3     79.6     80.4     83.1     84.5     84.6
     MX     88.3     88.2     88.0     89.9     94.2     90.2     90.6     91.6
     SM   2081.8   2046.9   2067.7   1999.1   2067.2   2071.1   2099.6   2122.8
     AV     86.7     85.3     86.2     83.3     86.1     86.3     87.5     88.5
```

D.4.2.3 DOE-2 Hourly Report of Indoor Temperature of the Energy Efficiency Strategy 2(Improve the 2nd Floor Ceiling Insulation: Upgrade R-11 to R-28)

```
1CASE STUDY HOUSE:THE JEERASAK'S HOUSE,  Model Improvement Strategy 2            DOE-2.1E-119  Thu Feb  5 15:09:20 2004SDL RUN  1
 Increase 2nd floor's ceiling insulation
 SYSTEM-REPORT-1  = HOURLY-REPORT                                                                                    PAGE260 -  1
 ---------------------------------------------------------------------------------------------------------------------------------
        SPACE1-1 SPACE1-2 SPACE1-3 SPACE2-1 SPACE2-2 SPACE2-3 SPACE2-4 SPACE-AT

        ZONE     ZONE     ZONE     ZONE     ZONE     ZONE     ZONE     ZONE
        TEMP     TEMP     TEMP     TEMP     TEMP     TEMP     TEMP     TEMP
        F        F        F        F        F        F        F        F

        ----( 6) ----( 6) ----( 6) ----( 6) ----( 6) ----( 6) ----( 6) ----( 6)
  917 1     85.4     84.2     85.6     79.7     80.5     85.5     86.4     84.4
  917 2     85.2     83.8     85.2     79.7     80.5     84.5     85.4     83.1
  917 3     85.0     83.4     85.0     79.7     80.5     84.0     85.1     82.2
  917 4     84.8     83.0     84.8     79.7     80.5     83.6     84.8     81.3
  917 5     84.6     82.5     84.6     79.6     80.4     83.1     84.6     80.3
  917 6     85.0     82.1     84.4     79.6     80.5     83.1     84.5     87.9
  917 7     85.6     82.1     84.4     79.7     80.5     83.2     84.7     95.7
  917 8     86.0     82.4     84.6     82.4     88.2     83.4     85.4    101.6
  917 9     86.3     83.1     85.2     83.9     90.5     84.5     87.2    106.2
  91710     87.0     83.9     85.8     85.4     92.3     85.4     88.2    110.5
  91711     87.6     84.8     86.3     86.7     93.2     86.2     89.1    113.8
  91712     87.8     85.6     86.7     87.8     94.0     87.0     89.6    116.2
  91713     88.0     86.4     87.1     88.9     94.4     87.8     90.1    113.6
  91714     88.2     87.3     87.4     89.7     94.7     88.6     90.5    112.0
  91715     88.3     87.9     87.6     90.1     94.6     89.1     90.8    106.2
  91716     88.1     88.2     87.8     90.2     94.4     90.5     90.9    101.6
  91717     87.8     88.3     87.9     90.1     94.1     89.7     90.9     98.5
  91718     88.0     88.2     88.0     90.1     93.7     89.6     90.9     96.3
  91719     87.8     88.2     88.1     79.8     80.6     89.4     90.9     94.5
  91720     87.6     87.5     87.0     79.9     80.7     88.2     87.5     93.2
  91721     87.2     87.0     86.8     79.9     80.6     87.6     87.2     91.6
  91722     87.1     86.6     86.6     79.9     80.6     87.2     86.9     90.5
  91723     86.8     86.3     86.5     79.8     80.6     86.8     86.7     89.5
  91724     86.7     86.0     86.3     79.8     80.5     86.5     86.4     88.3
0 DAILY SUMMARY (SEP 17)
     MN     84.6     82.1     84.4     79.6     80.4     83.1     84.5     80.3
     MX     88.3     88.3     88.1     90.2     94.7     90.5     90.9    116.2
     SM   2082.2   2048.7   2069.6   2002.2   2071.1   2074.7   2104.8   2319.0
     AV     86.8     85.4     86.2     83.4     86.3     86.4     87.7     96.6
```

D.4.2.4 DOE-2 Hourly Report of Indoor Temperature of the Energy Efficiency Strategy 3-1(Improve Wall Insulation: 4” Light-weight Concrete Block Wall)

```
1CASE STUDY HOUSE:THE JEERASAK'S HOUSE,  Model Improvement Strategy 3-1          DOE-2.1E-119  Thu Feb  5 16:59:58 2004SDL RUN  1
  4" Light Weight Concrete Wall
 SYSTEM-REPORT-1  = HOURLY-REPORT                                                                                    PAGE260 -  1
 ---------------------------------------------------------------------------------------------------------------------------------
        SPACE1-1 SPACE1-2 SPACE1-3 SPACE2-1 SPACE2-2 SPACE2-3 SPACE2-4 SPACE-AT

        ZONE     ZONE     ZONE     ZONE     ZONE     ZONE     ZONE     ZONE
        TEMP     TEMP     TEMP     TEMP     TEMP     TEMP     TEMP     TEMP
        F        F        F        F        F        F       F        F

        ----( 6) ----( 6) ----( 6) ----( 6) ----( 6) ----( 6) ----( 6) ----( 6)
  917 1     85.5     82.8     85.6     79.7     80.4     84.7     87.2     84.3
  917 2     85.3     82.2     85.3     79.7     80.4     83.9     86.5     83.0
  917 3     85.2     81.6     85.1     79.6     80.4     83.2     86.1     82.1
  917 4     85.0     81.2     84.9     79.6     80.4     82.6     85.8     81.2
  917 5     84.9     80.7     84.7     79.6     80.4     82.1     85.5     80.2
  917 6     85.7     80.3     84.9     79.7     80.5     82.6     86.3     87.9
  917 7     86.8     81.2     85.2     79.7     80.6     83.6     87.5     96.0
  917 8     87.2     82.7     85.4     84.1     92.2     84.6     88.7    102.0
  917 9     87.3     84.2     86.3     86.0     93.7     85.9     90.1    106.7
  91710     88.0     85.8     86.6     87.8     94.2     87.2     90.8    111.1
  91711     88.3     87.2     86.9     89.0     94.1     88.3     91.2    114.5
  91712     88.4     88.4     87.1     90.4     94.3     89.5     91.7    116.9
  91713     88.5     89.7     87.4     91.7     94.8     90.8     92.1    114.4
  91714     88.5     90.6     87.7     92.6     95.0     91.8     92.5    112.6
  91715     88.4     90.7     87.9     92.7     94.7     92.0     92.6    106.7
  91716     88.0     90.2     88.0     92.3     93.8     93.3     92.5    102.0
  91717     87.5     89.4     88.0     91.5     92.8     91.6     92.2     98.6
  91718     87.7     88.6     87.9     90.9     91.9     90.9     92.0     96.4
  91719     87.4     88.0     87.8     79.9     80.5     90.0     91.9     94.5
  91720     87.2     87.1     86.7     79.9     80.5     88.9     89.7     93.0
  91721     86.9     86.4     86.5     79.9     80.5     88.0     89.1     91.5
  91722     86.8     85.7     86.3     79.8     80.5     87.3     88.6     90.3
  91723     86.6     85.2     86.2     79.8     80.4     86.7     88.2     89.3
  91724     86.4     84.7     86.1     79.8     80.4     86.2     87.8     88.2
0 DAILY SUMMARY (SEP 17)
     MN     84.9     80.3     84.7     79.6     80.4     82.1     85.5     80.2
     MX     88.5     90.7     88.0     92.7     95.0     93.3     92.6    116.9
     SM   2087.4   2054.6   2074.4   2025.8   2077.6   2095.9   2146.7   2323.3
     AV     87.0     85.6     86.4     84.4     86.6     87.3     89.4     96.8
```

D.4.2.5 DOE-2 Hourly Report of Indoor Temperature of the Energy Efficiency Strategy 3-2 (Improve Wall Insulation: 6” Light-weight Concrete Block Wall)

```
1CASE STUDY HOUSE:THE JEERASAK'S HOUSE,  Model Improvement Strategy 3-2          DOE-2.1E-119  Thu Feb  5 16:47:21 2004SDL RUN  1
  6" Light Weight Concrete Wall
 SYSTEM-REPORT-1  = HOURLY-REPORT                                                                                   PAGE260 -  1
 ---------------------------------------------------------------------------------------------------------------------------------
        SPACE1-1 SPACE1-2 SPACE1-3 SPACE2-1 SPACE2-2 SPACE2-3 SPACE2-4 SPACE-AT

        ZONE     ZONE     ZONE     ZONE     ZONE     ZONE     ZONE     ZONE
        TEMP     TEMP     TEMP     TEMP     TEMP     TEMP     TEMP     TEMP
        F        F        F        F        F        F        F        F

        ----( 6) ----( 6) ----( 6) ----( 6) ----( 6) ----( 6) ----( 6) ----( 6)
  917 1     85.7     83.1     85.8     79.7     80.5     85.2     87.9     84.5
  917 2     85.5     82.5     85.4     79.7     80.4     84.4     87.3     83.2
  917 3     85.4     82.0     85.2     79.7     80.4     83.8     87.0     82.2
  917 4     85.3     81.6     85.1     79.6     80.4     83.3     86.7     81.3
  917 5     85.1     81.2     84.9     79.6     80.4     82.8     86.4     80.4
  917 6     85.9     80.7     85.0     79.7     80.5     83.2     86.9     88.0
  917 7     86.8     81.5     85.2     79.7     80.6     84.1     87.9     96.1
  917 8     87.2     82.7     85.4     83.7     90.7     84.9     89.0    102.1
  917 9     87.3     84.1     86.2     85.5     92.2     86.0     90.0    106.8
  91710     87.9     85.5     86.5     87.2     92.9     87.1     90.6    111.2
  91711     88.3     86.7     86.7     88.5     93.0     88.1     91.1    114.6
  91712     88.3     87.8     86.9     89.9     93.4     89.2     91.5    117.0
  91713     88.4     89.0     87.2     91.2     93.9     90.3     91.9    114.5
  91714     88.4     89.9     87.5     92.1     94.2     91.2     92.3    112.7
  91715     88.3     90.0     87.7     92.3     94.0     91.5     92.4    106.9
  91716     88.0     89.6     87.8     92.0     93.2     92.9     92.4    102.1
  91717     87.5     89.0     87.8     91.3     92.4     91.4     92.1     98.8
  91718     87.7     88.3     87.7     90.8     91.6     90.7     91.9     96.5
  91719     87.5     87.8     87.7     79.9     80.5     90.0     91.9     94.7
  91720     87.3     87.1     86.6     80.0     80.5     89.1     90.2     93.2
  91721     87.0     86.5     86.4     79.9     80.5     88.3     89.7     91.7
  91722     86.9     85.8     86.3     79.9     80.5     87.7     89.2     90.5
  91723     86.6     85.4     86.2     79.8     80.5     87.1     88.9     89.5
  91724     86.5     84.9     86.1     79.8     80.4     86.6     88.5     88.3
0 DAILY SUMMARY (SEP 17)
     MN     85.1     80.7     84.9     79.6     80.4     82.8     86.4     80.4
     MX     88.4     90.0     87.8     92.3     94.2     92.9     92.4    117.0
     SM   2088.7   2052.8   2073.3   2021.5   2067.6   2098.5   2153.8   2326.8
     AV     87.0     85.5     86.4     84.2     86.2     87.4     89.7     97.0
```

D.4.2.6 DOE-2 Hourly Report of Indoor Temperature of the Energy Efficiency Strategy 3-3 (Improve Wall Insulation: 4” Light-weight Concrete Block Wall with Exterior Insulation)

```
1CASE STUDY HOUSE:THE JEERASAK'S HOUSE,  Model Improvement Strategy 3-3          DOE-2.1E-119  Sun Feb 15 18:59:37 2004SDL RUN  1
  4" L-W-Concrete Wall + Ex Insu.
 SYSTEM-REPORT-1  = HOURLY-REPORT                                                                                    PAGE260 -  1
 ---------------------------------------------------------------------------------------------------------------------------------
        SPACE1-1 SPACE1-2 SPACE1-3 SPACE2-1   SPACE2-2 SPACE2-3 SPACE2-4 SPACE-AT

        ZONE     ZONE     ZONE     ZONE       ZONE     ZONE     ZONE     ZONE
        TEMP     TEMP     TEMP     TEMP       TEMP     TEMP     TEMP     TEMP
        F        F        F        F          F        F        F        F

        ----( 6) ----( 6) ----( 6) ----( 6) ----( 6) ----( 6) ----( 6) ----( 6)
  917 1     85.9     83.1     86.0     79.7     80.5     85.7     88.9     84.7
  917 2     85.8     82.5     85.7     79.7     80.5     85.0     88.4     83.4
  917 3     85.7     82.1     85.5     79.7     80.4     84.5     88.0     82.4
  917 4     85.6     81.7     85.4     79.7     80.4     84.0     87.8     81.5
  917 5     85.5     81.3     85.3     79.6     80.4     83.5     87.5     80.6
  917 6     86.3     80.9     85.3     79.7     80.5     84.1     88.5     88.2
  917 7     87.1     81.9     85.4     79.7     80.6     85.0     89.5     96.2
  917 8     87.4     83.3     85.6     83.3     88.8     85.6     90.5    102.2
  917 9     87.4     84.5     86.1     84.9     90.1     86.4     90.9    107.0
  91710     88.0     85.9     86.4     86.6     90.8     87.4     91.3    111.4
  91711     88.3     87.0     86.6     87.8     91.1     88.3     91.7    114.8
  91712     88.3     88.0     86.8     89.2     91.7     89.3     92.2    117.2
  91713     88.4     89.1     87.1     90.6     92.4     90.4     92.6    114.7
  91714     88.4     89.8     87.3     91.5     92.8     91.1     92.9    113.0
  91715     88.3     89.7     87.5     91.8     92.7     91.2     92.9    107.1
  91716     88.0     89.0     87.6     91.5     92.2     92.9     92.7    102.4
  91717     87.5     88.3     87.7     91.0     91.5     91.2     92.4     99.0
  91718     87.7     87.6     87.6     90.6     91.0     90.6     92.2     96.8
  91719     87.5     87.2     87.6     79.9     80.5     89.9     92.3     94.9
  91720     87.4     86.7     86.6     80.0     80.6     89.3     90.9     93.4
  91721     87.1     86.1     86.4     79.9     80.5     88.6     90.5     91.9
  91722     87.0     85.6     86.3     79.9     80.5     88.0     90.1     90.8
  91723     86.8     85.2     86.2     79.8     80.5     87.5     89.9     89.7
  91724     86.7     84.8     86.1     79.8     80.4     87.1     89.6     88.6
0 DAILY SUMMARY (SEP 17)
     MN     85.5     80.9     85.3     79.6     80.4     83.5     87.5     80.6
     MX     88.4     89.8     87.7     91.8     92.8     92.9     92.9    117.2
     SM   2091.9   2051.1   2074.1   2016.1   2051.4   2106.5   2174.1   2331.9
     AV     87.2     85.5     86.4     84.0     85.5     87.8     90.6     97.2
```

D.4.2.7 DOE-2 Hourly Report of Indoor Temperature of the Energy Efficiency Strategy 3-4 (Improve Wall Insulation: 4” Light-weight Concrete Block Wall with Interior Insulation)

```
1CASE STUDY HOUSE:THE JEERASAK'S HOUSE,  Model Improvement Strategy 3-4          DOE-2.1E-119  Sun Feb 15 19:38:10 2004SDL RUN  1
  4" L-W-Concrete Wall + In Insu.
 SYSTEM-REPORT-1  = HOURLY-REPORT                                                                                   PAGE260 -  1
 ---------------------------------------------------------------------------------------------------------------------------------
        SPACE1-1 SPACE1-2 SPACE1-3 SPACE2-1 SPACE2-2 SPACE2-3 SPACE2-4 SPACE-AT SPACE-AT

        ZONE     ZONE     ZONE     ZONE     ZONE     ZONE     ZONE     ZONE     ZONE
        TEMP     TEMP     TEMP     TEMP     TEMP     TEMP     TEMP     TEMP     TEMP
        F        F        F        F        F        F        F        F        F

        ----( 6) ----( 6) ----( 6) ----( 6) ----( 6) ----( 6) ----( 6) ----( 6) ----( 6)
  917 1     85.9     83.2     86.1     79.7     80.5     85.7     89.2     84.6     90.3
  917 2     85.8     82.7     85.7     79.7     80.4     85.0     88.8     83.3     89.5
  917 3     85.7     82.3     85.6     79.7     80.4     84.4     88.5     82.4     88.6
  917 4     85.6     81.9     85.4     79.7     80.4     84.0     88.2     81.5     87.9
  917 5     85.5     81.5     85.3     79.6     80.4     83.5     88.0     80.5     87.3
  917 6     86.3     81.1     85.3     79.7     80.5     84.0     88.4     88.3     86.5
  917 7     87.2     81.8     85.4     79.7     80.6     84.9     89.1     96.4     89.9
  917 8     87.4     83.0     85.5     83.6     89.8     85.5     90.0    102.5     93.6
  917 9     87.4     84.2     86.2     85.4     91.3     86.4     90.5    107.2     96.5
  91710     88.0     85.6     86.4     87.2     91.9     87.4     91.0    111.6     99.0
  91711     88.3     86.7     86.7     88.5     92.0     88.4     91.4    115.0    101.5
  91712     88.3     87.7     86.9     90.0     92.6     89.5     91.9    117.4    103.5
  91713     88.4     88.7     87.2     91.4     93.2     90.5     92.3    114.8    105.2
  91714     88.4     89.5     87.4     92.3     93.6     91.3     92.5    113.0    104.6
  91715     88.3     89.5     87.7     92.5     93.3     91.4     92.7    107.1    104.2
  91716     87.9     89.0     87.7     92.1     92.6     93.1     92.6    102.3    101.9
  91717     87.5     88.4     87.8     91.4     91.8     91.4     92.4     98.9     99.9
  91718     87.7     87.7     87.7     90.9     91.1     90.7     92.2     96.7     98.4
  91719     87.5     87.4     87.7     79.9     80.5     90.0     92.3     94.8     97.4
  91720     87.4     86.8     86.7     80.0     80.5     89.3     91.2     93.3     96.5
  91721     87.1     86.3     86.5     79.9     80.5     88.6     90.9     91.8     95.7
  91722     87.0     85.7     86.4     79.9     80.5     88.1     90.5     90.7     94.9
  91723     86.8     85.3     86.3     79.8     80.5     87.6     90.3     89.7     94.2
  91724     86.7     84.9     86.2     79.8     80.4     87.1     90.0     88.5     93.6
0 DAILY SUMMARY (SEP 17)
     MN     85.5     81.1     85.3     79.6     80.4     83.5     88.0     80.5     86.5
     MX     88.4     89.5     87.8     92.5     93.6     93.1     92.7    117.4    105.2
     SM   2092.2   2051.0   2076.0   2022.2   2059.4   2108.0   2174.9   2332.3   2300.6
     AV     87.2     85.5     86.5     84.3     85.8     87.8     90.6     97.2     95.9
```

D.4.2.8 DOE-2 Hourly Report of Indoor Temperature of the Energy Efficiency Strategy 4 (Low-E Windows)

```
1CASE STUDY HOUSE:THE JEERASAK'S HOUSE, Model Improvement Strategy 4             DOE-2.1E-119  Mon Feb  2 22:02:54 2004SDL RUN  1
 Low-e window
 SYSTEM-REPORT-1  = HOURLY-REPORT                                                                                   PAGE260 -  1
 ---------------------------------------------------------------------------------------------------------------------------------
        SPACE1-1 SPACE1-2 SPACE1-3 SPACE2-1 SPACE2-2 SPACE2-3 SPACE2-4 SPACE-AT

        ZONE     ZONE     ZONE     ZONE     ZONE     ZONE     ZONE     ZONE
        TEMP     TEMP     TEMP     TEMP     TEMP     TEMP     TEMP     TEMP
        F        F        F        F        F        F        F        F

        ----( 6) ----( 6) ----( 6) ----( 6) ----( 6) ----( 6) ----( 6) ----( 6)
  917 1     85.1     84.3     85.6     79.7     80.5     85.6     86.4     84.1
  917 2     85.0     83.9     85.2     79.7     80.5     84.7     85.4     82.8
  917 3     84.8     83.5     84.9     79.7     80.5     84.2     85.1     81.8
  917 4     84.6     83.1     84.7     79.7     80.5     83.7     84.8     81.0
  917 5     84.4     82.7     84.5     79.7     80.5     83.3     84.6     80.0
  917 6     84.7     82.2     84.3     79.6     80.5     83.1     84.5     87.4
  917 7     85.0     82.2     84.3     79.7     80.5     83.2     84.7     95.1
  917 8     85.3     82.5     84.5     82.5     87.5     83.5     85.5    100.9
  917 9     85.6     83.2     85.1     83.9     89.9     84.6     87.2    105.4
  91710     86.3     84.0     85.7     85.5     91.7     85.4     88.3    109.6
  91711     86.8     84.8     86.2     86.7     92.8     86.2     89.2    112.9
  91712     87.0     85.6     86.6     87.9     93.6     87.0     89.8    115.2
  91713     87.3     86.4     86.9     89.0     94.1     87.9     90.3    112.7
  91714     87.5     87.2     87.3     89.8     94.4     88.6     90.7    111.0
  91715     87.6     87.8     87.5     90.2     94.4     89.1     90.9    105.4
  91716     87.5     88.1     87.7     90.4     94.3     90.5     91.0    100.9
  91717     87.3     88.3     87.8     90.3     94.0     89.7     91.0     97.8
  91718     87.5     88.2     87.9     90.3     93.6     89.7     91.0     95.7
  91719     87.3     88.2     88.0     79.9     80.6     89.5     91.0     94.0
  91720     87.1     87.5     86.9     80.0     80.7     88.2     87.6     92.5
  91721     86.8     87.1     86.7     79.9     80.6     87.7     87.3     91.0
  91722     86.6     86.6     86.5     79.9     80.6     87.3     87.0     89.9
  91723     86.4     86.3     86.4     79.9     80.6     87.0     86.7     88.9
  91724     86.2     86.0     86.2     79.8     80.6     86.6     86.5     87.8
0 DAILY SUMMARY (SEP 17)
     MN     84.4     82.2     84.3     79.6     80.5     83.1     84.5     80.0
     MX     87.6     88.3     88.0     90.4     94.4     90.5     91.0    115.2
     SM   2069.9   2049.5   2067.6   2003.6   2067.5   2076.3   2106.4   2303.9
     AV     86.2     85.4     86.2     83.5     86.1     86.5     87.8     96.0
```

D.4.2.9 DOE-2 Hourly Report of Indoor Temperature of the Energy Efficiency Strategy 5 (Shading Devices on Windows)

```
1CASE STUDY HOUSE:THE JEERASAK'S HOUSE, Model Improvement Strategy 5             DOE-2.1E-119  Thu Feb  5 23:34:36 2004SDL RUN  1
 Shading Devices on Windows
 SYSTEM-REPORT-1  = HOURLY-REPORT                                                                                   PAGE260 -  1
 ---------------------------------------------------------------------------------------------------------------------------------
        SPACE1-1 SPACE1-2 SPACE1-3 SPACE2-1 SPACE2-2 SPACE2-3 SPACE2-4 SPACE-AT

        ZONE     ZONE     ZONE     ZONE     ZONE     ZONE     ZONE     ZONE
        TEMP     TEMP     TEMP     TEMP     TEMP     TEMP     TEMP     TEMP
        F        F        F        F        F        F        F        F

        ----( 6) ----( 6) ----( 6) ----( 6) ----( 6) ----( 6) ----( 6) ----( 6)
  917 1     85.3     84.3     85.6     79.7     80.5     85.5     86.4     84.0
  917 2     85.1     83.9     85.2     79.7     80.5     84.6     85.4     82.7
  917 3     84.9     83.4     84.9     79.7     80.5     84.1     85.1     81.8
  917 4     84.8     83.0     84.7     79.7     80.5     83.6     84.8     80.9
  917 5     84.6     82.6     84.5     79.6     80.4     83.2     84.6     80.0
  917 6     84.9     82.2     84.3     79.6     80.5     83.2     84.5     87.4
  917 7     85.5     82.3     84.4     79.7     80.5     83.3     84.7     95.1
  917 8     85.9     82.5     84.6     82.5     87.6     83.6     85.5    100.9
  917 9     86.1     83.3     85.2     83.9     89.8     84.7     87.2    105.4
  91710     86.9     84.1     85.7     85.4     91.5     85.6     88.3    109.6
  91711     87.4     84.9     86.2     86.7     92.7     86.4     89.1    112.8
  91712     87.6     85.7     86.6     87.8     93.5     87.2     89.8    115.2
  91713     87.8     86.5     87.0     88.8     94.0     88.0     90.3    112.7
  91714     88.0     87.2     87.3     89.5     94.3     88.7     90.6    111.0
  91715     88.1     87.7     87.5     89.9     94.3     89.2     90.9    105.4
  91716     87.9     88.0     87.7     90.1     94.1     90.5     90.9    100.9
  91717     87.7     88.2     87.8     90.0     93.7     89.7     90.9     97.8
  91718     87.9     88.1     87.9     89.9     93.3     89.6     90.9     95.7
  91719     87.7     88.1     87.9     79.9     80.6     89.4     90.9     93.9
  91720     87.5     87.4     86.9     80.0     80.7     88.2     87.6     92.5
  91721     87.1     87.0     86.7     79.9     80.6     87.7     87.3     91.0
  91722     87.0     86.6     86.5     79.9     80.6     87.3     87.0     89.9
  91723     86.7     86.3     86.4     79.9     80.6     86.9     86.7     88.9
  91724     86.5     86.0     86.2     79.8     80.5     86.5     86.4     87.7
0 DAILY SUMMARY (SEP 17)
     MN     84.6     82.2     84.3     79.6     80.4     83.2     84.5     80.0
     MX     88.1     88.2     87.9     90.1     94.3     90.5     90.9    115.2
     SM   2078.8   2049.2   2067.6   2001.5   2065.9   2076.8   2105.9   2303.1
     AV     86.6     85.4     86.2     83.4     86.1     86.5     87.7     96.0
```

D.4.2.10 DOE-2 Hourly Report of Indoor Temperature of the Energy Efficiency Strategy 6-1 (High Thermal Mass Wall: 8” Brick)

```
1CASE STUDY HOUSE:THE JEERASAK'S HOUSE,  Model Improvement Strategy 6-1          DOE-2.1E-119  Fri Feb  6 02:02:32 2004SDL RUN  1
 High Thermal Mass Walls - 8"
 SYSTEM-REPORT-1  = HOURLY-REPORT                                                                                   PAGE260 -  1
 ---------------------------------------------------------------------------------------------------------------------------------
        SPACE1-1 SPACE1-2 SPACE1-3 SPACE2-1 SPACE2-2 SPACE2-3 SPACE2-4 SPACE-AT

        ZONE     ZONE     ZONE     ZONE     ZONE     ZONE     ZONE     ZONE
        TEMP     TEMP     TEMP     TEMP     TEMP     TEMP     TEMP     TEMP
        F        F        F        F        F        F        F        F

        ----( 6) ----( 6) ----( 6) ----( 6) ----( 6) ----( 6) ----( 6) ----( 6)
  917 1     85.8     84.5     85.9     79.8     80.6     86.1     87.3     84.7
  917 2     85.7     84.3     85.5     79.8     80.7     85.3     86.4     83.5
  917 3     85.6     84.1     85.4     79.8     80.6     85.0     86.2     82.6
  917 4     85.5     84.0     85.2     79.7     80.6     84.8     86.0     81.8
  917 5     85.3     83.8     85.1     79.7     80.6     84.5     85.9     80.8
  917 6     85.7     83.5     85.0     79.7     80.6     84.7     85.8     88.2
  917 7     86.2     83.7     84.9     79.7     80.7     84.8     85.9     95.7
  917 8     86.3     83.9     84.9     82.9     87.0     84.9     86.2    101.2
  917 9     86.3     84.2     85.2     83.8     87.7     85.5     87.2    105.5
  91710     86.9     84.6     85.4     84.8     88.5     85.9     87.7    109.6
  91711     87.2     84.9     85.6     85.5     89.2     86.3     88.3    112.7
  91712     87.3     85.1     85.9     86.4     90.1     86.7     88.7    114.8
  91713     87.4     85.5     86.1     87.1     90.8     87.2     89.2    112.3
  91714     87.5     85.8     86.3     87.7     91.2     87.5     89.5    110.6
  91715     87.6     86.0     86.5     87.9     91.4     87.6     89.6    105.0
  91716     87.5     86.1     86.7     87.9     91.3     88.7     89.7    100.6
  91717     87.2     86.2     86.8     87.8     91.3     87.8     89.6     97.6
  91718     87.5     86.2     87.0     87.9     91.2     87.8     89.6     95.6
  91719     87.4     86.4     87.1     79.9     80.7     87.8     89.7     94.0
  91720     87.3     86.1     86.3     80.0     80.8     87.1     87.5     92.7
  91721     87.1     86.0     86.2     80.0     80.7     86.9     87.4     91.3
  91722     87.0     85.8     86.2     79.9     80.7     86.7     87.2     90.3
  91723     86.8     85.7     86.1     79.9     80.7     86.6     87.1     89.4
  91724     86.7     85.6     86.0     79.9     80.7     86.4     86.9     88.3
0 DAILY SUMMARY (SEP 17)
     MN     85.3     83.5     84.9     79.7     80.6     84.5     85.8     80.8
     MX     87.6     86.4     87.1     87.9     91.4     88.7     89.7    114.8
     SM   2080.9   2042.1   2061.3   1987.6   2038.4   2072.8   2104.5   2308.9
     AV     86.7     85.1     85.9     82.8     84.9     86.4     87.7     96.2
```

D.4.2.11 DOE-2 Hourly Report of Indoor Temperature of the Energy Efficiency Strategy 6-2 (High Thermal Mass Wall: 12” Brick)

```
1CASE STUDY HOUSE:THE JEERASAK'S HOUSE,  Model Improvement Strategy 6-2          DOE-2.1E-119  Fri Feb  6 00:34:08 2004SDL RUN  1
 High Thermal Mass Walls - 12"
 SYSTEM-REPORT-1  = HOURLY-REPORT                                                                                   PAGE260 -  1
 ---------------------------------------------------------------------------------------------------------------------------------
        SPACE1-1 SPACE1-2 SPACE1-3 SPACE2-1 SPACE2-2 SPACE2-3 SPACE2-4 SPACE-AT

        ZONE     ZONE     ZONE     ZONE     ZONE     ZONE     ZONE     ZONE
        TEMP     TEMP     TEMP     TEMP     TEMP     TEMP     TEMP     TEMP
        F        F        F        F        F        F        F        F

        ----( 6) ----( 6) ----( 6) ----( 6) ----( 6) ----( 6) ----( 6) ----( 6)
  917 1     85.8     84.4     85.8     79.8     80.6     86.0     87.5     84.9
  917 2     85.7     84.3     85.4     79.8     80.7     85.5     86.8     83.7
  917 3     85.7     84.2     85.3     79.8     80.6     85.3     86.6     82.9
  917 4     85.6     84.1     85.3     79.8     80.6     85.1     86.5     82.1
  917 5     85.5     84.0     85.2     79.8     80.6     84.9     86.4     81.2
  917 6     85.9     83.8     85.1     79.8     80.7     85.2     86.5     88.5
  917 7     86.4     84.1     85.1     79.8     80.7     85.4     86.5     96.0
  917 8     86.6     84.4     85.0     83.2     87.7     85.5     86.8    101.5
  917 9     86.6     84.7     85.4     84.1     88.1     86.1     87.7    105.7
  91710     87.0     85.0     85.5     84.9     88.4     86.4     88.1    109.7
  91711     87.3     85.2     85.6     85.5     88.6     86.7     88.4    112.8
  91712     87.3     85.4     85.8     86.1     89.0     87.0     88.7    114.9
  91713     87.4     85.6     85.9     86.7     89.5     87.3     89.0    112.3
  91714     87.4     85.7     86.0     87.0     89.8     87.4     89.1    110.6
  91715     87.4     85.7     86.1     87.2     89.8     87.4     89.2    105.0
  91716     87.2     85.6     86.2     87.0     89.7     88.3     89.2    100.6
  91717     87.0     85.5     86.3     86.8     89.7     87.3     89.1     97.6
  91718     87.2     85.4     86.4     86.7     89.6     87.1     89.1     95.6
  91719     87.1     85.5     86.5     79.9     80.6     87.0     89.2     94.0
  91720     87.0     85.3     85.8     80.0     80.7     86.5     87.6     92.8
  91721     86.8     85.2     85.8     80.0     80.7     86.4     87.4     91.4
  91722     86.8     85.1     85.7     80.0     80.7     86.3     87.3     90.4
  91723     86.6     85.1     85.7     79.9     80.7     86.2     87.2     89.5
  91724     86.6     85.1     85.7     79.9     80.7     86.1     87.1     88.5
0 DAILY SUMMARY (SEP 17)
     MN     85.5     83.8     85.0     79.8     80.6     84.9     86.4     81.2
     MX     87.4     85.7     86.5     87.2     89.8     88.3     89.2    114.9
     SM   2079.8   2038.1   2056.9   1983.4   2028.6   2072.7   2107.2   2312.0
     AV     86.7     84.9     85.7     82.6     84.5     86.4     87.8     96.3
```

D.4.2.12 DOE-2 Hourly Report of Indoor Temperature of Combination A

```
1CASE STUDY HOUSE:THE JEERASAK'S HOUSE, COMBINATION A                          DOE-2.1E-119  Sun Feb 15 23:35:44 2004SDL RUN  1
 Strategy 2+(3-4)+7+8+9
 SYSTEM-REPORT-1  = HOURLY-REPORT                                                                                   PAGE260 -  1
 ---------------------------------------------------------------------------------------------------------------------------------
        SPACE1-1 SPACE1-2 SPACE1-3 SPACE2-1 SPACE2-2 SPACE2-3 SPACE2-4 SPACE-AT

        ZONE     ZONE     ZONE     ZONE     ZONE     ZONE     ZONE     ZONE
        TEMP     TEMP     TEMP     TEMP     TEMP     TEMP     TEMP     TEMP
        F        F        F        F        F        F        F        F

        ----( 6) ----( 6) ----( 6) ----( 6) ----( 6) ----( 6) ----( 6) ----( 6)
  917 1     85.5     82.9     85.6     79.7     80.5     85.2     88.0     85.1
  917 2     85.4     82.4     85.3     79.7     80.4     84.6     87.7     83.8
  917 3     85.3     82.0     85.1     79.7     80.4     84.0     87.4     82.8
  917 4     85.2     81.6     85.0     79.7     80.4     83.6     87.2     81.9
  917 5     85.1     81.3     84.9     79.6     80.4     83.2     87.0     80.9
  917 6     85.9     80.8     84.9     79.7     80.5     83.7     87.5     88.8
  917 7     86.7     81.6     85.0     79.7     80.6     84.5     88.1     97.1
  917 8     87.0     82.6     85.1     83.2     89.5     85.0     88.8    103.3
  917 9     87.0     83.7     85.7     84.8     90.9     85.8     89.2    108.1
  91710     87.6     85.0     86.0     86.5     91.4     86.7     89.5    112.6
  91711     88.0     86.0     86.2     87.7     91.3     87.5     89.8    116.1
  91712     87.9     87.0     86.4     89.0     91.7     88.4     90.1    118.5
  91713     88.0     87.9     86.6     90.3     92.2     89.4     90.4    115.9
  91714     88.0     88.7     86.9     91.2     92.5     90.1     90.7    114.1
  91715     87.9     88.7     87.1     91.4     92.3     90.3     90.8    108.0
  91716     87.6     88.3     87.1     91.1     91.6     92.1     90.8    103.1
  91717     87.2     87.7     87.2     90.5     90.8     90.5     90.6     99.7
  91718     87.3     87.1     87.1     90.1     90.2     89.8     90.6     97.4
  91719     87.1     86.7     87.1     79.9     80.5     89.2     90.6     95.5
  91720     86.9     86.2     86.2     79.9     80.5     88.5     89.7     94.1
  91721     86.6     85.7     86.0     79.9     80.5     87.9     89.4     92.5
  91722     86.6     85.2     85.9     79.9     80.5     87.3     89.1     91.4
  91723     86.4     84.8     85.8     79.8     80.5     86.9     88.9     90.3
  91724     86.3     84.5     85.7     79.8     80.4     86.5     88.7     89.1
0 DAILY SUMMARY (SEP 17)
     MN     85.1     80.8     84.9     79.6     80.4     83.2     87.0     80.9
     MX     88.0     88.7     87.2     91.4     92.5     92.1     90.8    118.5
     SM   2082.4   2038.4   2064.0   2012.5   2050.6   2090.8   2140.6   2350.1
     AV     86.8     84.9     86.0     83.9     85.4     87.1     89.2     97.9
```

D.4.2.13 DOE-2 Hourly Report of Indoor Temperature of Combination B

```
1CASE STUDY HOUSE:THE JEERASAK'S HOUSE, Combination B                          DOE-2.1E-119  Mon Feb 16 00:12:19 2004SDL RUN  1
 Combi A  + Strategy 4
 SYSTEM-REPORT-1  = HOURLY-REPORT                                                                                   PAGE260 -  1
 ----------------------------------------------------------------------------------------------------------------------------------
        SPACE1-1 SPACE1-2 SPACE1-3 SPACE2-1 SPACE2-2 SPACE2-3 SPACE2-4 SPACE-AT

        ZONE     ZONE     ZONE     ZONE     ZONE     ZONE     ZONE     ZONE
        TEMP     TEMP     TEMP     TEMP     TEMP     TEMP     TEMP     TEMP
        F        F        F        F        F        F        F        F

        ----( 6) ----( 6) ----( 6) ----( 6) ----( 6) ----( 6) ----( 6) ----( 6)
  917 1     84.8     82.9     85.0     79.7     80.5     85.0     87.6     85.1
  917 2     84.7     82.4     84.7     79.7     80.5     84.5     87.2     83.8
  917 3     84.6     82.1     84.6     79.7     80.4     84.0     87.0     82.8
  917 4     84.5     81.8     84.5     79.7     80.4     83.6     86.8     81.9
  917 5     84.5     81.5     84.4     79.7     80.4     83.3     86.6     80.9
  917 6     85.0     81.1     84.4     79.7     80.5     83.5     86.9     88.8
  917 7     85.5     81.7     84.5     79.7     80.6     84.1     87.5     97.1
  917 8     85.8     82.5     84.6     82.8     87.6     84.5     88.2    103.3
  917 9     85.8     83.5     85.1     84.2     88.7     85.2     88.5    108.1
  91710     86.3     84.5     85.3     85.7     89.1     85.9     88.9    112.6
  91711     86.6     85.4     85.5     86.8     89.3     86.6     89.1    116.1
  91712     86.6     86.1     85.7     88.0     89.7     87.4     89.4    118.5
  91713     86.7     87.0     85.9     89.2     90.2     88.2     89.7    115.9
  91714     86.7     87.6     86.1     90.1     90.5     88.8     89.9    114.0
  91715     86.7     87.7     86.3     90.4     90.5     89.0     90.0    108.0
  91716     86.5     87.4     86.4     90.3     90.1     91.0     90.0    103.1
  91717     86.2     86.9     86.5     90.0     89.6     89.6     89.9     99.6
  91718     86.3     86.4     86.4     89.7     89.1     89.0     89.9     97.4
  91719     86.1     86.2     86.4     79.9     80.5     88.5     90.0     95.5
  91720     86.0     85.8     85.5     80.0     80.6     88.0     89.1     94.1
  91721     85.7     85.4     85.4     79.9     80.5     87.4     88.8     92.5
  91722     85.6     84.9     85.3     79.9     80.5     87.0     88.5     91.4
  91723     85.5     84.6     85.2     79.9     80.5     86.6     88.3     90.3
  91724     85.4     84.3     85.1     79.8     80.5     86.2     88.1     89.1
0 DAILY SUMMARY (SEP 17)
     MN     84.5     81.1     84.4     79.7     80.4     83.3     86.6     80.9
     MX     86.7     87.7     86.5     90.4     90.5     91.0     90.0    118.5
     SM   2058.1   2029.4   2049.2   2004.5   2030.8   2076.8   2125.9   2349.6
     AV     85.8     84.6     85.4     83.5     84.6     86.5     88.6     97.9
```

D.4.2.14 DOE-2 Hourly Report of Indoor Temperature of Combination C

```
1CASE STUDY HOUSE:THE JEERASAK'S HOUSE, Combination C                          DOE-2.1E-119  Mon Feb 16 01:29:01 2004SDL RUN  1
 Combination A  + Strategy 5
 SYSTEM-REPORT-1  = HOURLY-REPORT                                                                                   PAGE260 -  1
 ---------------------------------------------------------------------------------------------------------------------------------
        SPACE1-1 SPACE1-2 SPACE1-3 SPACE2-1 SPACE2-2 SPACE2-3 SPACE2-4 SPACE-AT

        ZONE     ZONE     ZONE     ZONE     ZONE     ZONE     ZONE     ZONE
        TEMP     TEMP     TEMP     TEMP     TEMP     TEMP     TEMP     TEMP
        F        F        F        F        F        F        F        F

        ----( 6) ----( 6) ----( 6) ----( 6) ----( 6) ----( 6) ----( 6) ----( 6)
  917 1     85.7     83.4     85.7     79.7     80.5     85.4     88.1     85.1
  917 2     85.6     82.9     85.4     79.7     80.5     84.8     87.7     83.8
  917 3     85.5     82.5     85.2     79.7     80.4     84.2     87.5     82.8
  917 4     85.4     82.1     85.1     79.7     80.4     83.8     87.3     81.9
  917 5     85.3     81.8     85.0     79.6     80.4     83.3     87.1     80.9
  917 6     86.2     82.0     85.0     79.7     80.5     84.2     87.5     88.9
  917 7     87.0     82.6     85.1     79.7     80.6     85.0     88.1     97.1
  917 8     87.3     83.7     85.3     83.3     87.7     85.5     88.8    103.3
  917 9     87.2     84.9     85.8     85.0     88.7     86.3     89.2    108.1
  91710     87.9     86.3     86.0     86.8     89.3     87.2     89.5    112.6
  91711     88.2     87.4     86.3     88.3     89.9     88.1     89.8    116.1
  91712     88.2     88.5     86.5     89.9     90.7     89.1     90.2    118.5
  91713     88.2     89.4     86.7     91.2     91.5     90.0     90.5    115.9
  91714     88.2     89.9     87.0     92.0     92.0     90.7     90.7    114.1
  91715     88.1     89.8     87.2     92.0     91.8     90.7     90.9    108.0
  91716     87.8     89.3     87.3     91.6     91.2     92.5     90.9    103.1
  91717     87.4     88.6     87.4     90.9     90.5     90.8     90.7     99.7
  91718     87.5     87.9     87.3     90.4     89.9     90.2     90.6     97.4
  91719     87.3     87.5     87.3     79.9     80.6     89.5     90.7     95.5
  91720     87.1     87.0     86.3     79.9     80.6     88.8     89.8     94.1
  91721     86.8     86.4     86.2     79.9     80.5     88.1     89.4     92.5
  91722     86.8     85.9     86.0     79.9     80.5     87.6     89.2     91.4
  91723     86.6     85.5     85.9     79.8     80.5     87.1     89.0     90.3
  91724     86.5     85.1     85.8     79.8     80.5     86.7     88.7     89.1
0 DAILY SUMMARY (SEP 17)
     MN     85.3     81.8     85.0     79.6     80.4     83.3     87.1     80.9
     MX     88.2     89.9     87.4     92.0     92.0     92.5     90.9    118.5
     SM   2087.6   2060.4   2066.7   2018.5   2039.6   2099.6   2142.1   2350.2
     AV     87.0     85.8     86.1     84.1     85.0     87.5     89.3     97.9
```

D.4.2.15 DOE-2 Hourly Report of Indoor Temperature of Combination D

```
1CASE STUDY HOUSE:THE JEERASAK'S HOUSE,  Combination D                          DOE-2.1E-119  Mon Feb 16 02:15:35 2004SDL RUN  1
 Combination A + Strategies 4 and 5
 SYSTEM-REPORT-1  = HOURLY-REPORT                                                                                    PAGE260 -  1
 ---------------------------------------------------------------------------------------------------------------------------------
        SPACE1-1 SPACE1-2 SPACE1-3 SPACE2-1 SPACE2-2 SPACE2-3 SPACE2-4 SPACE-AT

        ZONE     ZONE     ZONE     ZONE     ZONE     ZONE     ZONE     ZONE
        TEMP     TEMP     TEMP     TEMP     TEMP     TEMP     TEMP     TEMP
        F        F        F        F        F        F        F        F

        ----( 6) ----( 6) ----( 6) ----( 6) ----( 6) ----( 6) ----( 6) ----( 6)
  917 1     84.9     83.2     85.1     79.7     80.5     85.2     87.6     85.1
  917 2     84.8     82.8     84.8     79.7     80.5     84.6     87.2     83.8
  917 3     84.7     82.4     84.7     79.7     80.5     84.2     87.0     82.8
  917 4     84.6     82.1     84.6     79.7     80.4     83.8     86.8     81.9
  917 5     84.5     81.7     84.5     79.7     80.4     83.4     86.6     80.9
  917 6     85.1     81.8     84.5     79.7     80.5     83.8     87.0     88.8
  917 7     85.7     82.3     84.6     79.7     80.6     84.3     87.5     97.1
  917 8     85.9     83.2     84.7     82.9     86.5     84.8     88.2    103.3
  917 9     85.9     84.2     85.1     84.3     87.4     85.4     88.5    108.1
  91710     86.5     85.2     85.3     85.8     88.0     86.2     88.9    112.6
  91711     86.8     86.2     85.5     87.1     88.5     86.9     89.1    116.1
  91712     86.7     87.0     85.7     88.4     89.1     87.7     89.4    118.5
  91713     86.8     87.7     85.9     89.6     89.7     88.5     89.7    115.9
  91714     86.8     88.2     86.2     90.5     90.2     89.0     89.9    114.0
  91715     86.8     88.2     86.3     90.7     90.2     89.2     90.1    108.0
  91716     86.6     87.9     86.4     90.6     89.8     91.2     90.1    103.1
  91717     86.3     87.4     86.5     90.2     89.4     89.7     89.9     99.7
  91718     86.4     86.9     86.5     89.9     89.0     89.2     89.9     97.4
  91719     86.2     86.6     86.5     79.9     80.6     88.7     90.0     95.5
  91720     86.1     86.2     85.6     80.0     80.6     88.1     89.1     94.1
  91721     85.8     85.7     85.5     79.9     80.5     87.5     88.8     92.5
  91722     85.7     85.3     85.4     79.9     80.5     87.1     88.6     91.4
  91723     85.6     84.9     85.3     79.9     80.5     86.7     88.4     90.3
  91724     85.5     84.6     85.2     79.8     80.5     86.3     88.2     89.1
0 DAILY SUMMARY (SEP 17)
     MN     84.5     81.7     84.5     79.7     80.4     83.4     86.6     80.9
     MX     86.8     88.2     86.5     90.7     90.2     91.2     90.1    118.5
     SM   2060.6   2041.7   2050.3   2007.2   2024.5   2081.5   2126.5   2349.6
     AV     85.9     85.1     85.4     83.6     84.4     86.7     88.6     97.9
```

D.4.2.16 DOE-2 Hourly Report of Indoor Temperature of Combination E

```
1CASE STUDY HOUSE:THE JEERASAK'S HOUSE,  Combination E                          DOE-2.1E-119  Sun Apr  4 19:52:22 2004LDL RUN  1
Combination D + Shading from PV-T
 SYSTEM-REPORT-1  = HOURLY-REPORT                                                                                    PAGE260 -  1
 ---------------------------------------------------------------------------------------------------------------------------------
        SPACE1-1 SPACE1-2 SPACE1-3 SPACE2-1 SPACE2-2 SPACE2-3 SPACE2-4 SPACE-AT

        ZONE     ZONE     ZONE     ZONE     ZONE     ZONE     ZONE     ZONE
        TEMP     TEMP     TEMP     TEMP     TEMP     TEMP     TEMP     TEMP
        F        F        F        F        F        F        F        F

        ----( 6) ----( 6) ----( 6) ----( 6) ----( 6) ----( 6) ----( 6) ----( 6)
  917 1     84.9     83.1     85.0     79.7     80.5     85.1     87.5     84.9
  917 2     84.8     82.7     84.7     79.7     80.5     84.5     87.2     83.7
  917 3     84.7     82.3     84.6     79.7     80.5     84.1     86.9     82.9
  917 4     84.6     82.0     84.5     79.7     80.4     83.7     86.7     82.1
  917 5     84.5     81.7     84.4     79.7     80.4     83.3     86.5     81.1
  917 6     85.1     81.8     84.4     79.7     80.5     83.8     86.9     90.1
  917 7     85.7     82.3     84.5     79.7     80.6     84.3     87.5     96.8
  917 8     85.9     83.2     84.6     82.8     86.5     84.8     88.2    101.7
  917 9     85.9     84.1     85.1     84.3     87.4     85.4     88.5    105.4
  91710     86.4     85.2     85.3     85.7     87.9     86.1     88.8    109.1
  91711     86.7     86.1     85.5     87.0     88.4     86.8     89.0    111.8
  91712     86.7     86.9     85.7     88.3     89.0     87.6     89.3    113.8
  91713     86.8     87.6     85.9     89.5     89.6     88.3     89.5    111.6
  91714     86.8     88.1     86.1     90.3     90.0     88.9     89.7    110.0
  91715     86.8     88.1     86.3     90.6     90.0     89.1     89.9    104.9
  91716     86.6     87.8     86.3     90.4     89.7     91.1     89.9    100.8
  91717     86.3     87.3     86.5     90.0     89.2     89.6     89.8     97.9
  91718     86.4     86.8     86.4     89.7     88.8     89.1     89.7     96.0
  91719     86.2     86.5     86.4     79.9     80.6     88.5     89.8     94.3
  91720     86.1     86.1     85.5     80.0     80.6     88.0     89.0     93.1
  91721     85.8     85.7     85.4     79.9     80.5     87.4     88.7     91.7
  91722     85.7     85.2     85.3     79.9     80.5     87.0     88.4     90.7
  91723     85.6     84.9     85.2     79.9     80.5     86.6     88.2     89.8
  91724     85.5     84.5     85.1     79.8     80.5     86.2     88.1     88.8
0 DAILY SUMMARY (SEP 17)
     MN     84.5     81.7     84.4     79.7     80.4     83.3     86.5     81.1
     MX     86.8     88.1     86.5     90.6     90.0     91.1     89.9    113.8
     SM   2060.3   2040.1   2049.0   2005.9   2023.2   2079.0   2123.8   2313.3
     AV     85.8     85.0     85.4     83.6     84.3     86.6     88.5     96.4
```

D.4.2.17 DOE-2 Hourly Report of Indoor Temperature of Combinations F and G

Combinations F and G had PV or PV-T^2 panels covered the whole area of the roof. DOE-2 hourly report below is the effect of PV or PV-T^2 panels to the indoor temperature of Combinations F and G.

```
1CASE STUDY HOUSE:THE JEERASAK'S HOUSE,  Combination F                          DOE-2.1E-119  Sun Apr  4 20:53:29 2004SDL RUN  1
 Combination D +PV
 SYSTEM-REPORT-1  = HOURLY-REPORT                                                                                   PAGE260 -  1
 ---------------------------------------------------------------------------------------------------------------------------------
        SPACE1-1 SPACE1-2 SPACE1-3 SPACE2-1 SPACE2-2 SPACE2-3 SPACE2-4 SPACE-AT

        ZONE     ZONE     ZONE     ZONE     ZONE     ZONE     ZONE     ZONE
        TEMP     TEMP     TEMP     TEMP     TEMP     TEMP     TEMP     TEMP
        F        F        F        F        F        F        F        F

        ----( 6) ----( 6) ----( 6) ----( 6) ----( 6) ----( 6) ----( 6) ----( 6)
  917 1     84.8     82.9     84.7     79.7     80.5     84.6     87.0     83.1
  917 2     84.7     82.5     84.5     79.7     80.5     84.1     86.7     82.3
  917 3     84.6     82.1     84.4     79.7     80.5     83.7     86.5     81.8
  917 4     84.6     81.8     84.3     79.7     80.4     83.3     86.3     81.3
  917 5     84.5     81.5     84.2     79.7     80.4     83.0     86.2     80.8
  917 6     85.0     81.6     84.2     79.7     80.5     83.5     86.5     82.5
  917 7     85.6     82.1     84.3     79.7     80.6     83.9     87.0     86.3
  917 8     85.8     82.9     84.4     82.6     86.2     84.3     87.6     88.6
  917 9     85.9     83.8     84.8     83.9     87.0     84.8     87.9     90.5
  91710     86.4     84.8     85.0     85.3     87.5     85.5     88.1     92.4
  91711     86.7     85.7     85.2     86.4     87.8     86.2     88.3     93.7
  91712     86.6     86.4     85.3     87.6     88.3     86.8     88.5     95.0
  91713     86.7     87.1     85.5     88.7     88.9     87.6     88.7     94.4
  91714     86.7     87.6     85.7     89.5     89.3     88.1     88.9     94.1
  91715     86.7     87.6     85.9     89.8     89.2     88.3     89.0     92.3
  91716     86.5     87.3     86.0     89.7     88.9     90.3     89.1     90.9
  91717     86.2     86.8     86.1     89.4     88.5     88.9     89.0     89.7
  91718     86.3     86.3     86.0     89.1     88.1     88.4     89.0     88.8
  91719     86.1     86.1     86.0     79.9     80.6     87.9     89.1     88.0
  91720     86.0     85.7     85.2     80.0     80.6     87.4     88.3     87.5
  91721     85.7     85.3     85.1     79.9     80.5     86.8     88.1     86.8
  91722     85.7     84.8     85.0     79.9     80.5     86.4     87.9     86.4
  91723     85.5     84.5     84.9     79.8     80.5     86.1     87.7     86.0
  91724     85.4     84.2     84.9     79.8     80.5     85.7     87.5     85.5
0 DAILY SUMMARY (SEP 17)
     MN     84.5     81.5     84.2     79.7     80.4     83.0     86.2     80.8
     MX     86.7     87.6     86.1     89.8     89.3     90.3     89.1     95.0
     SM   2058.6   2031.4   2041.8   1999.1   2016.4   2065.5   2109.1   2108.5
     AV     85.8     84.6     85.1     83.3     84.0     86.1     87.9     8
```

APPENDIX E

PREPARATION OF THE BANGKOK TRY FILE USING LS2TRY

The DOE-2 weather file used in this research was prepared and generated from a raw Bangkok weather data using the ATCHWEA and LS2TRY programs developed by Sreshthaputra (2002) and Bronson (1992) respectively. The procedure for generating the DOE-2 weather data file (TRY format) is illustrated in a flowchart in Figure E.1. There are mainly three phases in the procedure that need to perform: 1) Preparation of raw weather data using ATCHWEA and Microsoft Excel, 2) Preparation of weather data using LS2TRY, and 3) Packing weather data file using DOE-2 weather processor. Descriptions of each phase, which are explanations of Figure E.1, are elaborated in the following sections (E.1, E.2 and E.3).

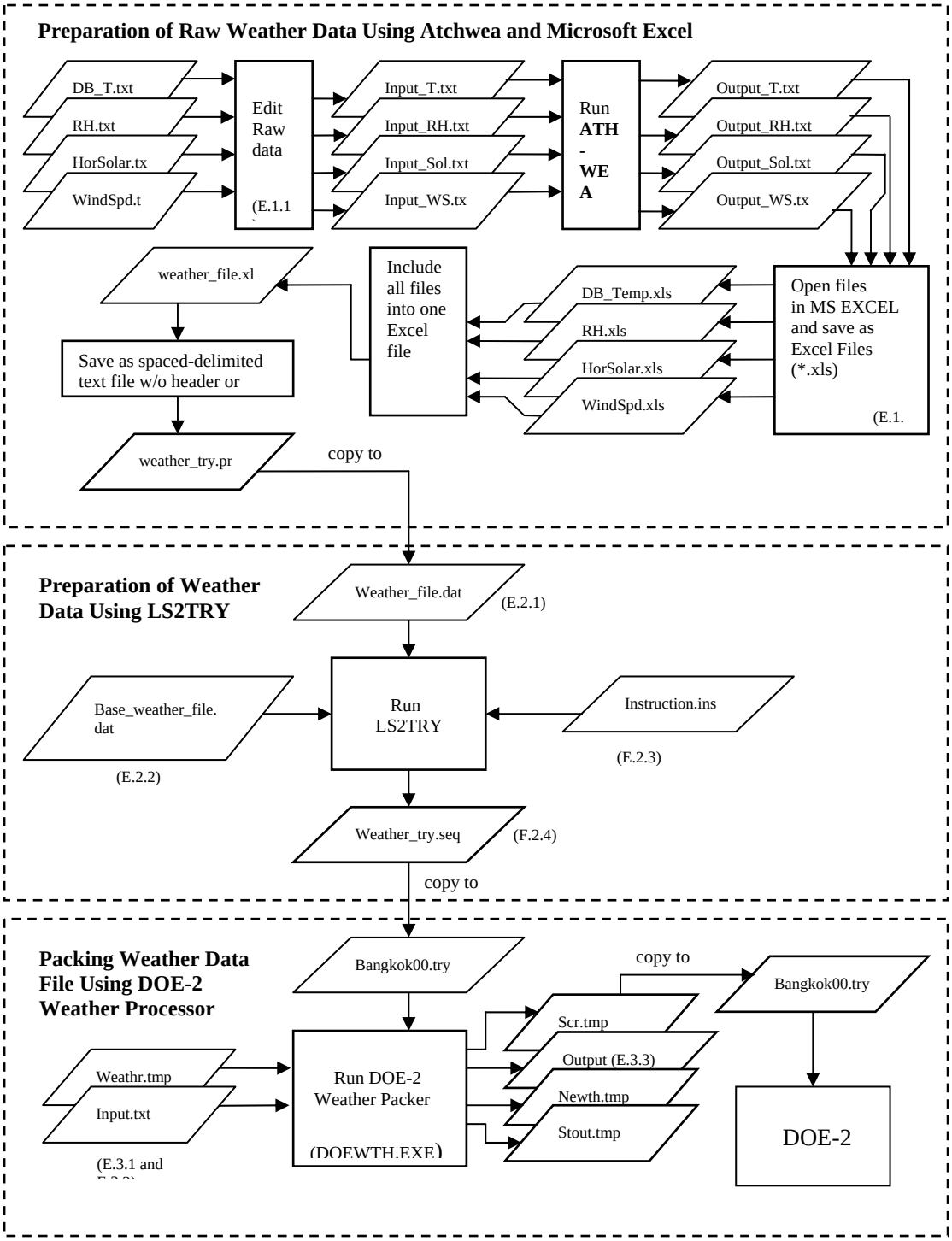


Figure E.1 *Methodology to Generate Thai Weather File (TRY Format) from Raw Weather Data.*

E.1. Preparation of Raw Weather Data Using ATCHWEA and Microsoft Excel

E.1.1 Editing Raw Weather Data

The Bangkok weather data 2000 was obtained from the Meteorological Department, Thailand. The Bangkok weather data includes dry-bulb temperature, relative humidity, global solar radiation, and wind speed. Each data was in text file. The following is an example of a month of the Bangkok dry-bulb temperature data of 2000. Data from 7:00 a.m. to 18:00 p.m. of the 6th to 25th was omitted in the example since the space constrain of the page.

Station: DON MUANG AIRPORT

January 2000
Dry bulb temperature (Celsius)

Day	0100	0200	0300	0400	0500	0600 ...	1900	2000	2100	2200	2300	2400	Mean
1	25.4	24.9	24.4	23.7	23.1	22.2 ...	28.9	28.5	27.9	27.4	26.9	26.0	27.6
2	25.2	24.8	23.2	23.1	22.8	23.2 ...	29.2	28.7	28.0	26.9	26.6	26.5	27.7
3	26.3	26.5	26.2	25.6	24.9	24.9 ...	29.7	28.5	28.4	28.1	27.1	27.2	28.6
4	26.5	26.1	25.0	24.7	24.0	23.3 ...	29.7	29.0	28.6	28.1	27.7	27.5	28.5
5	26.1	25.7	26.8	26.1	25.0	24.9 ...	30.3	29.5	29.1	28.3	28.0	27.4	29.4
.													
.													
.													
26	26.7	25.9	25.5	24.9	24.7	24.2 ...	28.7	28.5	27.6	26.4	25.3	25.7	27.7
27	24.7	24.0	22.7	21.5	21.7	20.5 ...	25.6	25.2	24.1	24.0	23.3	22.9	24.5
28	22.1	21.9	21.6	21.1	20.9	20.0 ...	25.5	24.4	23.6	23.7	22.2	22.0	23.8
29	21.5	20.9	20.2	20.3	20.1	19.6 ...	27.6	26.2	25.7	25.3	23.8	23.7	24.8
30	23.7	22.8	22.4	22.0	21.7	21.4 ...	25.6	25.2	24.8	23.9	23.4	23.4	24.5
31	23.8	23.0	22.3	22.4	22.0	22.0 ...	27.6	26.5	25.9	24.4	24.3	23.5	25.5
Mean	25.3	24.9	24.4	24.1	23.6	23.4 ...	28.6	27.6	27.0	26.4	25.9	25.7	27.4

Bangkok weather data is hourly data that is arranged in monthly table with headings, footings and daily mean on the far right column shown in the format above. Preparation of the weather data proceeded in stage. First, eliminate the headings, footings and the daily mean column, using a text editor program. After the headings and footings were removed, the data were saved and opened in Microsoft (MS) Excel. In the MS Excel, the Bangkok weather data was then converted to the proper units for use by the DOE-2 weather packer. Table E.1 shows the original units of the Bangkok weather data, units used in DOE-2 weather file, and unit conversions. Then, each climatic element was saved in text format (space delimited) and ready to run with Atchwea program.

Table E.1

Unit Conversions of the Weather Data

Climatic Elements	Original Units of Weahter Data	Unit Conversions	New Units of Weahter Data
Dry-bulb temperature	°C	[1]multiply by 9/5 and add 32	°F
Relative Humidity	%	-	%
Solar Radiation	10^{-2} MJ/m^2	[2]multiply by 2.7	W/m^2
Wind Speed	Knot	[1]multiply by 1.152	mph

[1] ASHRAE (2001) pp. 37.2

[2] SERI (2002)

E.1.2 Running Atchwea

Atchwea is the program that is used to convert weather data in table form into time-series data. Running Atchwea program needs weather data that was prepared in Section E.1.1. be in the same directory of the program. The weather data needs also to be renamed as INPUT.TXT. Then at the DOS prompt in the Atchwea's directory, the program is run by calling the program followed by INPUT.TXT, for example: "C:\ATCHWEA>ATCHWEA INPUT.TXT". After the run, the program generated a new file named "OUTPUT.TXT". This file is the weather data that is in time-series format. The output is shown in section E.1.3. Source code of ATCHWEA, which was written in FORTRAN, is shown below.

```
      PROGRAM ATCHWEA

      Integer V0,D,N

      Print*, '*** PROGRAM ATCHWEA ***'
      Print*, '***   AUGUST,2000   ***'
      Print*, '* ATCH SRESHTHAPUTRA *'
      Print*, ' '
      Print*, 'How Many Days in a Year?'
      Read*,D

C>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>
C
C    This program is used for converting
C    3D weather data into time-series data.
C
```

```
C>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>

        open (unit=10,file='INPUT.TXT',status='OLD')
        open (unit=11,file='OUTPUT.TXT',status='NEW')
        print*, 'READING INPUT DATA'
        N=1
        write(11,5)'Day of Year','Day of Month','Hour','value'
        do 12 count=1,D
        read (10,*) V0,V1,V2,V3,V4,V5,V6,V7,V8,V9,V10,V11,V12,
        &                       V13,V14,V15,V16,V17,V18,V19,V20,V21,V22,V23,V24

        Print*,'WRITING OUTPUT FILE'

        write(11,15) N,V0,'0100',V1
        write(11,15) N,V0,'0200',V2
        write(11,15) N,V0,'0300',V3
        write(11,15) N,V0,'0400',V4
        write(11,15) N,V0,'0500',V5
        write(11,15) N,V0,'0600',V6
        write(11,15) N,V0,'0700',V7
        write(11,15) N,V0,'0800',V8
        write(11,15) N,V0,'0900',V9
        write(11,15) N,V0,'1000',V10
        write(11,15) N,V0,'1100',V11
        write(11,15) N,V0,'1200',V12
        write(11,15) N,V0,'1300',V13
        write(11,15) N,V0,'1400',V14
        write(11,15) N,V0,'1500',V15
        write(11,15) N,V0,'1600',V16
        write(11,15) N,V0,'1700',V17
        write(11,15) N,V0,'1800',V18
        write(11,15) N,V0,'1900',V19
        write(11,15) N,V0,'2000',V20
        write(11,15) N,V0,'2100',V21
        write(11,15) N,V0,'2200',V22
        write(11,15) N,V0,'2300',V23
        write(11,15) N,V0,'2400',V24


        N=N+1
 12     continue

  5     format(1X,1X,A11,3X,A12,3X,A4,7X,A5)
 15     format(1X,3X,I3,12X,I2,10X,A4,5X,F7.2)
        print*,'DONE'

        END
```

E.1.3 Outputs from ATCHWEA

An example of OUTPUT.TXT is shown below. There four columns in the output file. The first three columns from left are titled as below. The last column is the weather data that was converted into time-series format. In the example, the last column is the Bangkok dry-bulb temperature data of 2000 listed from the first hour of the year to the last hour of the year.

Day of Year	Day of Month	Hour	value
1	1	0100	77.72
1	1	0200	76.82
1	1	0300	75.92
1	1	0400	74.66
1	1	0500	73.58
1	1	0600	71.96
1	1	0700	71.06
1	1	0800	76.64
1	1	0900	79.88
1	1	1000	83.48
1	1	1100	85.46
1	1	1200	87.98
.			
.			
.			
366	31	1300	89.06
366	31	1400	90.14
366	31	1500	88.34
366	31	1600	88.16
366	31	1700	88.16
366	31	1800	85.64
366	31	1900	83.66
366	31	2000	79.70
366	31	2100	80.06
366	31	2200	78.26
366	31	2300	78.08
366	31	2400	76.82

E.1.4 Including All Weather Files into One Excel File

Output files of the four climatic elements, which are dry-bulb temperature, relative humidity, solar radiation, and wind speed, were combined into one file in the Excel–one column for each element.

E.2 Preparation of Weather Data Using LS2TRY

E.2.1 Weather_file.dat

RAW WEATHER DATA FILE: WEATER_FILE.DAT

```
44444   1   1   72 72001 3653.0417   100  86.00  77.72    0.00   0.00
44444   1   1   72 72001 3653.0833   200  88.00  76.82    0.00   0.00
44444   1   1   72 72001 3653.1250   300  91.00  75.92    0.00   0.00
44444   1   1   72 72001 3653.1667   400  94.00  74.66    0.00   0.00
44444   1   1   72 72001 3653.2083   500  94.00  73.58    0.00   0.00
44444   1   1   72 72001 3653.2500   600  97.00  71.96   67.50   0.00
44444   1   1   72 72001 3653.2917   700  97.00  71.06  137.70   0.00
44444   1   1   72 72001 3653.3333   800  80.00  76.64  310.50   0.00
44444   1   1   72 72001 3653.3750   900  67.00  79.88  504.90   0.00
44444   1   1   72 72001 3653.4167  1000  56.00  83.48  653.40   5.76
44444   1   1   72 72001 3653.4583  1100  53.00  85.46  739.80   5.76
44444   1   1   72 72001 3653.5000  1200  45.00  87.98  756.00   5.76
44444   1   1   72 72001 3653.5417  1300  45.00  89.78  726.30   2.30
44444   1   1   72 72001 3653.5833  1400  41.00  91.94  607.50   2.30
44444   1   1   72 72001 3653.6250  1500  48.00  89.06  437.40   2.30
44444   1   1   72 72001 3653.6667  1600  43.00  90.14  232.20   4.61
44444   1   1   72 72001 3653.7083  1700  47.00  89.42   59.40   4.61
44444   1   1   72 72001 3653.7500  1800  62.00  86.18    0.00   4.61
44444   1   1   72 72001 3653.7917  1900  67.00  84.02    0.00   2.30
44444   1   1   72 72001 3653.8333  2000  69.00  83.30    0.00   2.30
44444   1   1   72 72001 3653.8750  2100  71.00  82.22    0.00   2.30
44444   1   1   72 72001 3653.9167  2200  74.00  81.32    0.00   1.15
44444   1   1   72 72001 3653.9583  2300  79.00  80.42    0.00   1.15
44444   1   1   72 72001 3654.0000  2400  85.00  78.80    0.00   1.15
```

E.2.2 Base_weather_file.dat

BASE_WEATHER_FILE.DAT

```
3333306306106018000329700009999999999999999999999999999999999999999    1997010100
3333306206106018000329700009999999999999999999999999999999999999999    1997010101
3333306206106018000229700009999999999999999999999999999999999999999    1997010102
3333306206106018000229700009999999999999999999999999999999999999999    1997010103
3333306106005918000229700009999999999999999999999999999999999999999    1997010104
3333306005905918000229700009999999999999999999999999999999999999999    1997010105
3333305905905818000229700009999999999999999999999999999999999999999    1997010106
3333306005905918000229700009999999999999999999999999999999999999999    1997010107
3333306106005918000229700009999999999999999999999999999900100000    1997010108
3333306306005918000329700009999999999999999999999999999900320002    1997010109
3333306606205918000529700009999999999999999999999999999900820020    1997010110
3333306906306018000429700009999999999999999999999999999901330092    1997010111
3333307106506118000329700009999999999999999999999999999901070030    1997010112
3333307106506218000229700009999999999999999999999999999900770007    1997010113
3333307306506218000329700009999999999999999999999999999901090078    1997010114
3333307206506218000429700009999999999999999999999999999900330002    1997010115
3333307106506218000429700009999999999999999999999999999900040000    1997010116
3333306906506318000529700009999999999999999999999999999999999999    1997010117
3333306706506418000329700009999999999999999999999999999999999999    1997010118
```

```
333330660650641800032970000999999999999999999999999999999999999999    1997010119
333330650650641800022970000999999999999999999999999999999999999999    1997010120
333330650650651800022970000999999999999999999999999999999999999999    1997010121
333330650650651800022970000999999999999999999999999999999999999999    1997010122
333330650650651800032970000999999999999999999999999999999999999999    1997010123
```

E.2.3 Instruction.ins

INSTRUCTION FILE: INSTRUCTION.INS

```
105.0  100.6 13.9 14.68 91.   301.  44444 180.
Y Y Y Y Y Y Y
```

E.2.4 Weather_try.seq

LS2TRY OUTPUT: WEATHER_TRY.SEQ (BANGKOK00.TRY or WEATHR.TMP)

```
444440780740731800002997000999999999999999999999999999999900000000    1972010100
444440770730731800002997000999999999999999999999999999999900000000    1972010101
444440760730731800002997000999999999999999999999999999999900000000    1972010102
444440750730731800002997000999999999999999999999999999999900000000    1972010103
444440740720721800002997000999999999999999999999999999999900000000    1972010104
444440720710711800002997000999999999999999999999999999999900000000    1972010105
444440710700701800002997000999999999999999999999999999999900440384    1972010106
444440770710701800002997000999999999999999999999999999999900980272    1972010107
444440800710681800002997000999999999999999999999999999999901600264    1972010108
444440830710661800052997000999999999999999999999999999999902070255    1972010109
444440850710661800052997000999999999999999999999999999999902350242    1972010110
444440880710641800052997000999999999999999999999999999999902400219    1972010111
444440900720661800022997000999999999999999999999999999999902300207    1972010112
444440920720651800022997000999999999999999999999999999999901930162    1972010113
444440890730671800022997000999999999999999999999999999999901390103    1972010114
444440900720651800042997000999999999999999999999999999999900740032    1972010115
444440890730671800042997000999999999999999999999999999999900190002    1972010116
444440860750721800042997000999999999999999999999999999999900000000    1972010117
444440840750721800022997000999999999999999999999999999999900000000    1972010118
444440830740721800022997000999999999999999999999999999999900000000    1972010119
444440820740721800022997000999999999999999999999999999999900000000    1972010120
444440810740721800012997000999999999999999999999999999999900000000    1972010121
444440800750731800012997000999999999999999999999999999999900000000    1972010122
444440790750741800012997000999999999999999999999999999999900000000    1972010123
```

E.3 Packing Weather Data File Using DOE-2 Weather Processor

DOE-2 weather processor requires two input files: WEATHR.TMP and INPUT.TMP. WEATHR.TMP is the output file from LS2TRY. INPUT.TMP is an instruction file that tells the weather processor what functions to perform. INPUT.TMP also supplies additional information that is needed to perform in the packing process. Detailed description of the input file is in E.3.1.

E.3.1 Instruction File

INSTRUCTION FILE: BANGKOK00.INS (INPUT.TMP)

```
PACK
BANGKOK 2000
TRY    44444  -999     7 13.09 100.630-BITSOLAR     4 20.  0.025
0.56  0.54  0.58  0.45  0.52  0.49  0.44  0.48  0.44  0.41  0.56  0.57
-999.
END
```

Calculation of Monthly Average Clearness Index is presented in section E.3.2.

E.3.2 Calculation of Monthly Average Clearness Index

Table E.1 shows calculation of clearness index of Bangkok 2000.

Table E.1

Unit Conversions of *the Weather Data*.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Monthly Average Daily Extraterrestrial Radiation at Bangkok (MJ/m^2)	30.50	33.28	36.24	37.96	38.13	37.88	37.85	37.81	36.63	34.00	30.96	29.50
Measured Monthly Average Daily Global Radiation at Bangkok, 2000 (MJ/m^2)	16.96	17.96	20.89	16.98	19.90	18.42	16.73	17.98	16.30	14.00	17.22	16.73
Monthly Average Clearness Index (K_T bar)	0.56	0.54	0.58	0.45	0.52	0.49	0.44	0.48	0.44	0.41	0.56	0.57

E.3.3 DOE-2 Weather Packer Outputs

```
                    DOE-2.1E-B20 WEATHER UTILITY PROGRAM

                          INPUT VERIFICATION

RUN TYPE PACK
-------------

     STATION NAME          BANGKOK 2000
     TAPE TYPE             TRY
     STATION NUMBER        44444
     TIME ZONE             7
     LATITUDE              13.090
     LONGITUDE             100.600
     WORD SIZE             30-BIT
     FILE TYPE             SOLAR
     INTERP INTERVAL       4
     MAX TEMPCHANGE        20.000
     SOIL DIFFUSIVITY      0.025
     CLEARNESS NUMBER ( 1)   0.560
     CLEARNESS NUMBER ( 2)   0.540
     CLEARNESS NUMBER ( 3)   0.580
     CLEARNESS NUMBER ( 4)   0.450
     CLEARNESS NUMBER ( 5)   0.520
     CLEARNESS NUMBER ( 6)   0.490
     CLEARNESS NUMBER ( 7)   0.440
     CLEARNESS NUMBER ( 8)   0.480
     CLEARNESS NUMBER ( 9)   0.440
     CLEARNESS NUMBER (10)   0.410
     CLEARNESS NUMBER (11)   0.560
     CLEARNESS NUMBER (12)   0.570
```

APPENDIX F

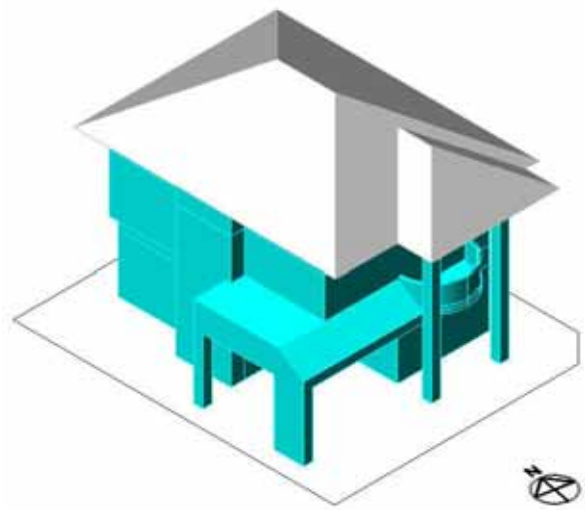
F-CHART AND PV F-CHART INPUT DATA AND RESULTS

In the analysis of supplemental thermal and electrical energies from the hybrid PV-T^2 collector system using F-Chart and PV F-Chart, the available installation area, which was the roof area, needed to be defined. Figure F.1 shows available area on the roof of the case-study house for installation of the PV-T^2 or PV arrays. Table F.1 shows gross roof areas on each side of the roof versus PV array areas. The PV array areas were obtained from number of PV panels shown in Figure F.1 multiplied by PV module area (11.3 ft^2). Table F.1 also shows the percentage of the total PV area to the gross roof area which is approximately 77 percent.

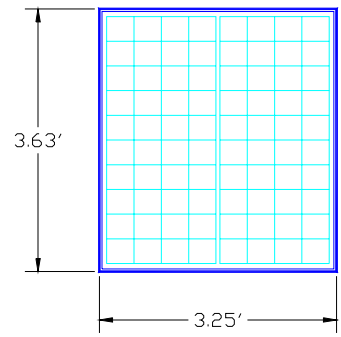
TABLE F.1

The Case-Study House's Roof Area and PV Array Area

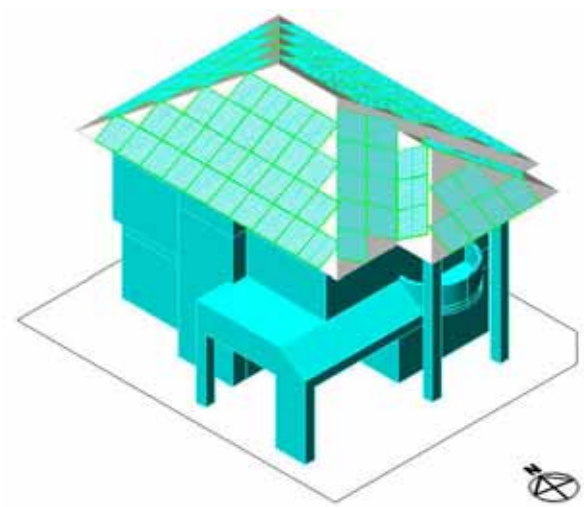
Roof Sides	Gross Roof Area (ft^2)			Max. of Number of PV panels		
	Main Hip	Front Hip	Total	Main Hip	Front Hip	Total
North	246	N/A	246	16	0	16
South	148	98	246	9	6	15
East	389	52	441	28	3	31
West	389	52	441	28	3	31
Total	**1172**	**202**	**1374**	**81**	**12**	**93**
	PV Array Area (ft^2)			PV Area to The Gross Area (%)		
North	181	0	181	73.6	N/A	73.6
South	102	68	170	68.9	69.4	69.1
East	317	34	351	81.5	65.4	79.6
West	317	34	351	81.5	65.4	79.6
Total	**917**	**136**	**1053**	**78.2**	**67.3**	**76.6**



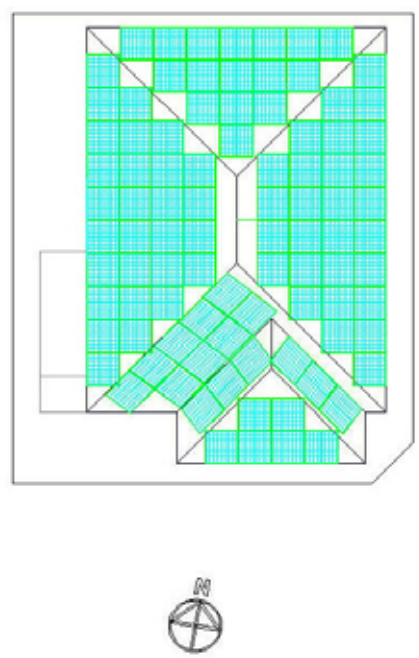
(a) Isometric View of The Case-Study House



(b) Photovoltaic Panel: Solarex MSX120



(c) Isometric View of The Case-Study House with the Hybrid PV-T^2 or PV arrays



(d) Plan View of The Case-Study with with the Hybrid PV-T^2 or PV arrays

Figure F.1 *Case-Study House and Available Roof Area for Installation of the PV panels*

F.1 Analysis of Thermal Energy Produced by the Hybrid PV-T^2 Collector System Using F-Chart

F.1.1 Input Data for the Analysis in the F-Chart Program

The solar thermal collector system, which is part of the hybrid PV-T^2 collector system, is showed in the Figure F.2. The PV-T^2 collector was considered as an unglazed flat-plate solar collector, thus this type of solar collector was chosen for the analysis of solar thermal collection of the hybrid PV-T^2 collector. The input collector parameters and input system parameter used in the F-CHART are presented in Figure F.2 and Figure F.3 respectively.

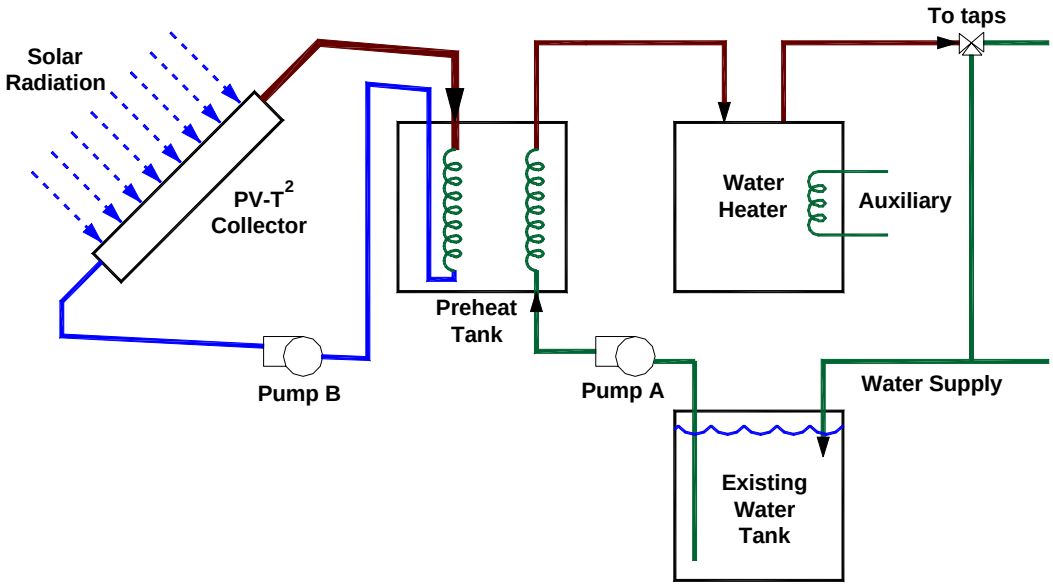


Figure F.2 *Schematic Diagram of the Hybrid PV-T^{2}System. This Diagram illustrates only components of thermal energy collection for domestic hot water supply.*

TABLE F.2

Input Collector Parameters used in the F-Chart

Pameter Number	Collector Parameters	Roof Sides		Units
		South	West	
1	Number of collector panels	15	11	panel
2	Collector panel area	11.31	11.31	ft^2
3	FR*UL (test slope)	5.62	5.62	$Btu/hr{\cdot}ft^2{\cdot}°F$
4	FR*TAU*ALPHA (test intercept)	0.45	0.45	
5	Collector slope	30	30	Degree
6	Collector azimuth (South=0)	-10	80	Degree
7	Inicdence angle mod TYPE(8-10)	8	8	
8	Number of glazings	0	0	
9	Inc angle modifier constant	0	0	
10	Inc angle modifier value(s)	N/A	N/A	
11	Collector flowrate/area	11	11	$lb/hr{\cdot}ft^2$
12	Collector fluid specific heat	1	1	Btu/lb·°F
13	Modify test values (1=Y,2=N)	2	2	
14	Test collector flowrate/area	N/A	N/A	$lb/hr{\cdot}ft^2$
15	Test fluid specific heat	N/A	N/A	Btu/lb·°F

TABLE F.3

Input System Parameters used in the F-Chart

Pameter Number	System Parameters	Roof Sides		Units
		South	West	
1	City call number	346	346	
2	Water storage volume	320	230	Gallons
3	Building UA (0 for DHW only)	0	0	Btu/hr·°F
4	Fuel (1=EL,2=NG,3=OIL,4=OTHER)	1	1	
5	Efficiency of fuel usage	100	100	%
6	Domestic hot water (1=Y,2=N)	1	1	
7	Daily hot water usage	100	100	Gallons
8	Water set temperature	140	140	°F
9	Environment temperature	88	88	°F
10	DHW storage tank size	160	120	Gallons
11	UA of aux storage tank.	1.27	1.27	Btu/hr·°F
12	Pipe heat loss (1=Y,2=N)	1	1	
13	Inlet pipe UA	5	5	Btu/hr·°F
14	Outlet pipe UA	5	5	Btu/hr·°F
15	Relative load HX size	2	2	
16	Collector-storage HX (1=Y,2=N)	1	1	
17	Tank side flowrate/area	11	11	lb/hr·ft^2
18	Heat exchanger effectiveness	0.5	0.5	

F.1.2 Results from the Analysis

F.1.2.1 Results from the South Facing Collectors

The hybrid PV-T^2 collectors were first chosen to install in the south side of the roof. The analysis was performed by varying the area of the collector from 22.6 ft^2 (2 panels) to the maximum available area, which was 170 ft^2 (26 panels) on the south side of the roof. Figure F.3

presents the results (Fraction of DHW loads or "F") versus collector area. Table 8.3 presets the results of 8th Run which used the maximum area of the south side roof. It can be seen in the Figure F.3 and Table F.3 that, with the maximum roof area on the south side, the system could supply the highest solar DHW in March (F = 0.87) and the lowest in July and October (F=0.63 and 0.64, respectively). To supply all DHW need, more collectors were installed on the west side of the roof. Next section presents the results from the west collectors.

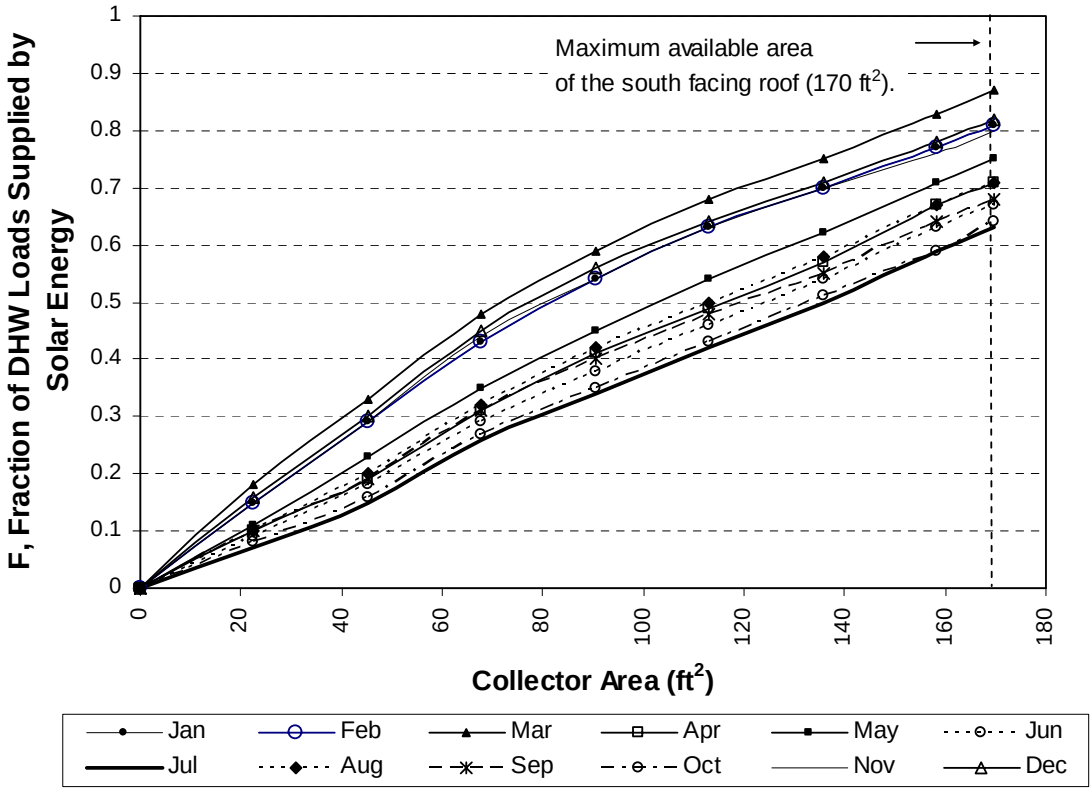


Figure F.3 *Fraction of Supplemental Solar DHW to the DHW Loads (F) of the South Facing Collector. The collector area ranges from 0 to the maximum collector area of the south facing roof (170 ft^2).*

TABLE F.3

Results from the Analysis of the Solar DHW: the 8th Run of South Facing Collectors

Month	Solar Energy MMBTU	DHW Load MMBTU	Auxiliary Energy MMBTU	F	Supplemental Solar DHW MMBTU
JAN	9	1.6	0.3	0.81	1.3
FEB	8.1	1.4	0.3	0.81	1.1
MAR	9.6	1.5	0.2	0.87	1.3
APR	6.9	1.4	0.4	0.71	1
MAY	7.7	1.5	0.4	0.75	1.1
JUN	6.8	1.5	0.5	0.67	1
JUL	6.5	1.5	0.6	0.63	0.9
AUG	7.4	1.5	0.4	0.71	1.1
SEP	7	1.5	0.5	0.68	1
OCT	6.7	1.6	0.6	0.64	1
NOV	8.8	1.6	0.3	0.8	1.3
DEC	9.2	1.6	0.3	0.82	1.3
Total/Avg.	93.8	18.1	4.7	0.74	13.4

F.1.2.2 Results from the West Facing Collectors

Figure F.4 presents the results (Fraction of DHW loads or “F”) versus collector area. Table F.4 presets the results of the 6th Run, which could sufficiently supply the total DHW need. It was required 11 panel (124 ft^2) of the collector as shown in Figure F.4. Table 8.5 presents the total solar DHW supplied by the south and west collectors.

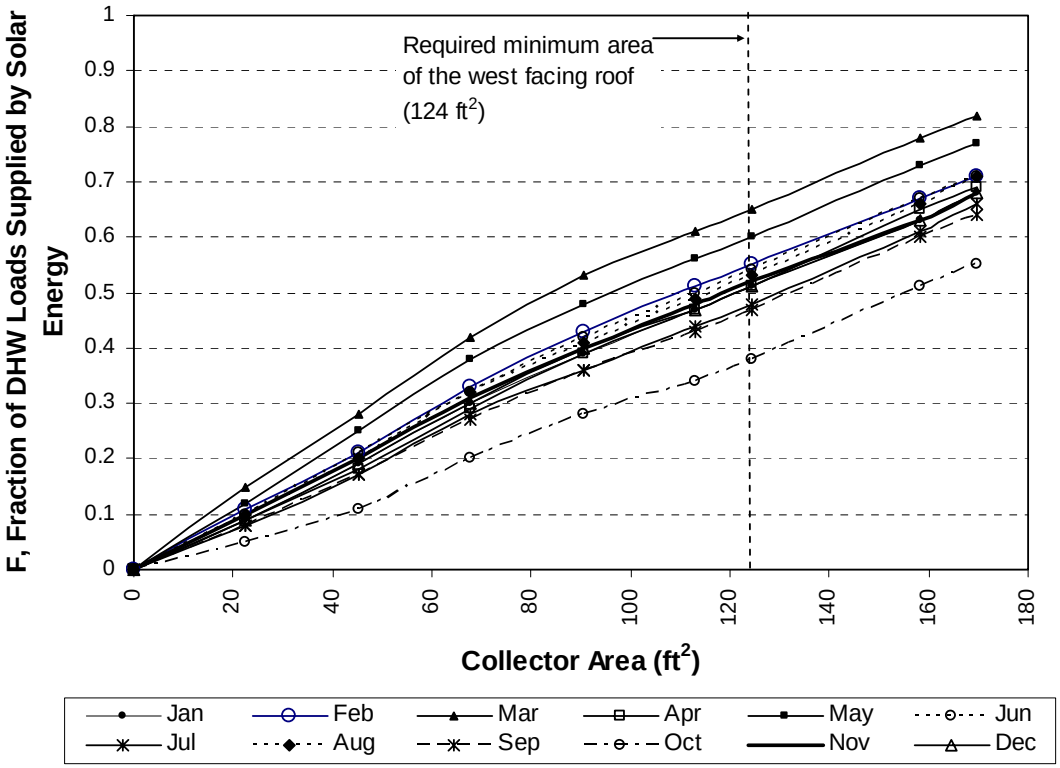


Figure F.4 *Fraction of Supplemental Solar DHW to the DHW Loads (F) of the West Facing Collectors*

TABLE F.4

Results from the Analysis of the Solar DHW: the 6th Run of the West Facing Collectors

Month	Solar Energy MMBTU	DHW Load MMBTU	Auxiliary Energy MMBTU	F	Supplemental Solar DHW MMBTU
JAN	5.5	1.6	0.8	0.51	0.8
FEB	5.3	1.4	0.6	0.55	0.8
MAR	6.7	1.5	0.5	0.65	1
APR	5.2	1.4	0.7	0.51	0.7
MAY	6.2	1.5	0.6	0.6	0.9
JUN	5.5	1.5	0.7	0.54	0.8
JUL	5.2	1.5	0.8	0.48	0.7
AUG	5.6	1.5	0.7	0.53	0.8
SEP	5	1.5	0.8	0.47	0.7
OCT	4.5	1.6	1	0.38	0.6
NOV	5.5	1.6	0.7	0.52	0.9
DEC	5.5	1.6	0.8	0.51	0.8
Total/Avg.	65.6	18.1	8.7	0.52	9.4

TABLE 8.5

Results from the Analysis of the Solar DHW: South and West Facing Collectors

Month	Supplemental Solar DHW			DHW	F
	South (MMBTU)	West (MMBTU)	Total (MMBTU)	Load (MMBTU)	(0-1)
JAN	1.3	0.8	2.1	1.6	1
FEB	1.1	0.8	1.9	1.4	1
MAR	1.3	1	2.3	1.5	1
APR	1	0.7	1.7	1.4	1
MAY	1.1	0.9	2	1.5	1
JUN	1	0.8	1.8	1.5	1
JUL	0.9	0.7	1.6	1.5	1
AUG	1.1	0.8	1.9	1.5	1
SEP	1	0.7	1.7	1.5	1
OCT	1	0.6	1.6	1.6	1
NOV	1.3	0.9	2.2	1.6	1
DEC	1.3	0.8	2.1	1.6	1
YR	13.4	9.4	22.8	18.1	1

F.2 Analysis of Electricity Generated by the Hybrid PV-T^2 Collector System Using PV-F Chart

The collector area of the hybrid PV-T^2 collector was determined by the required DHW need as presented in Section F.1. This section presents the results of the analysis of electricity produced by the south and west PV-T^2 collectors using PV-F CHART. Table F.6 presents input parameters for the south and west PV-T^2 collectors. The results of the analysis are presented in Table F.7. The annual electricity supplied by the PV-T^2 collectors (807.6 kWh) shown in Table F.7 was the annual electricity saving from the base-case's annual electricity use when it was installed with the Hybrid PV-T^2 system.

TABLE F.6

Input Parameters for the PV System:
South and West Facing Hybrid PV-T^2 Arrays

No.	Description	South Facing Array	West Facing Array	Unit	Remark
1	Cell temperature at NOCT conditions	47	47	°C	*
2	Array reference efficiency	0.114	0.114		**
3	Array reference temperature	25	25	°C	*
4	Array temperature coefficient*1000	0.5	0.5	1/°C	***
5	Power tracking efficiency	0.9	0.9		Default
6	Power conditioning efficiency	0.88	0.88		Default
7	Percent standard deviation of load	0	0	%	Default
8	Array area	15.77	11.56	m^2	Collector area
9	Area slope	30	30	degrees	Roof's slope
10	Array azimuth (South=0)	-10	80	degrees	

* Manufacture specification
** Calculated from manufacture specification and physical measurement of the array
*** Experimental value

TABLE F.7

Summary of Monthly and Annual Electricity Produced and Supplied by the South and West Hybrid PV-T^2 Arrays

Month	Load (kWh)	Elec. Produced by the PV-T^2 Array			Electricity Supplied by the PV-T^2 Arrays		Electricity Sell (kWh)	Electricity Purchase (kWh)
		South (PV-T^2) (kWh)	West (PV-T^2) (kWh)	Total (kWh)	(kWh)	%		
January	448	225	136	362	67.58	15.1	294	380
February	405	202	131	333	62.46	15.4	271	342
March	448	238	166	403	72.90	16.3	331	375
April	434	170	127	298	65.84	15.2	232	368
May	448	188	152	340	72.67	16.2	268	375
June	434	164	135	299	68.66	15.8	230	365
July	448	159	127	286	68.81	15.4	217	379
August	448	181	139	319	69.71	15.6	250	378
September	434	172	124	296	64.21	14.8	232	369
October	448	165	111	277	62.09	13.9	215	386
November	434	221	136	357	66.17	15.3	290	367
December	448	232	137	369	67.64	15.1	302	380
Year	5275	2317	1620	3937	**807.59**	15.3	3130	4467

F.3 Analysis of Electricity Generated by the PV System Using PV-F Chart

As present in Chapter VII, Section 7.3.11, Strategy 10 (Renewable Energy System 2) was installed with PV modules on all available area of the roof (1053 ft^2) without the presence of the Hybrid PV-T^2 collectors. This section presents the results of the analysis of electricity produced by the south, west, east, and north PV arrays using PV-F CHART. Table F.8 presents input parameters for the south and west PV collectors. The results of the analysis are presented in Table F.9. The annual electricity supplied by the PV collectors (1174.9 kWh) shown in Table F.9 was the annual electricity saving of the base-case's annual electricity use when it was installed with the PV system.

TABLE F.8

Input Parameters for the PV System: South, West, East, and North Facing PV Arrays

No.	Description	South Facing Array	West Facing Array	East Facing Array	North Facing Array	Unit	Remark
1	Cell temperature at NOCT conditions	47	47	47	47	°C	*
2	Array reference efficiency	0.114	0.114	0.114	0.114		**
3	Array reference temperature	25	25	25	25	°C	*
4	Array temperature coefficient*1000	4.3	4.3	4.3	4.3	1/°C	Default
5	Power tracking efficiency	0.9	0.9	0.9	0.9		Default
6	Power conditioning efficiency	0.88	0.88	0.88	0.88		Default
7	Percent standard deviation of load	0	0	0	0	%	Default
8	Array area	15.77	32.58	32.58	16.82	m^2	PV area
9	Area slope	30	30	30	30	degrees	Roof's slope
10	Array azimuth (South=0)	-10	80	-100	170	degrees	

* Manufacture specification

** Calculated from manufacture specification and physical measurement of the array

TABLE F.9

Summary of Monthly and Annual Electricity Produced and Supplied by the South, West, East, and North PV Arrays

Month	Load	Electricity Produced by the PV Arrays					Electricity Supplied by the PV Arrays		Electricity Sell	Electricity Purchase
		South	West	East	North	Total				
	(kWh)	(kWh)	(kWh)	(kWh)	(kWh)	(kWh)	(kWh)	%	(kWh)	(kWh)
January	448	202	348	300	111	961	87.30	19.5	873	361
February	405	182	333	301	125	940	85.73	21.2	855	319
March	448	211	415	394	181	1201	105.23	23.5	1096	343
April	434	155	325	323	163	966	100.34	23.1	866	333
May	448	171	384	396	212	1163	114.99	25.7	1048	333
June	434	150	346	360	197	1053	110.36	25.5	943	323
July	448	146	328	338	182	993	108.90	24.3	885	339
August	448	165	354	357	185	1060	108.37	24.2	952	340
September	434	157	318	309	150	934	95.97	22.1	838	338
October	448	151	288	270	121	829	86.64	19.3	743	361
November	434	199	348	303	116	964	87.12	20.1	877	346
December	448	208	351	297	106	960	85.86	19.2	875	362
Year	5275	2092	4136	3947	1848	12023	**1174.88**	22.3	10849	4100

F.4 Analysis of Electricity Generated by the Hybrid PV-T^2 Collector System and PV System Using PV-F Chart

As present in Chapter VII, Section 7.3.12, Strategy 11 (Renewable Energy System 3) was installed with both hybrid PV-T^2 collector system and PV system. The array area of the hybrid PV-T^2 collector system was the same as the area that was required to supply all DHW need in the case-study house which defined in Section F.1 The rest area of the roof was installed with the PV arrays. This section presents the results of the analysis of electricity produced by both systems using PV-F CHART. The input parameters of the Hybrid PV-T^2 system, which is the same as input parameters, are presented in Table F.6. Table F.10 presents input parameters for the PV system. The results of the analysis are presented in Table F.11. The annual electricity supplied by both systems (1174.9 kWh) shown in Table F.11 was the annual electricity saving of the base-case's annual electricity use when it was installed with the hybrid PV-T^2 collector system and PV system.

TABLE F.10

Input Parameters for the PV System:
West, East and North Facing PV Arrays

No.	Description	West Facing Array	East Facing Array	North Facing Array	Unit	Remark
1	Cell temperature at NOCT conditions	47	47	47	°C	*
2	Array reference efficiency	0.114	0.114	0.114		**
3	Array reference temperature	25	25	25	°C	*
4	Array temperature coefficient*1000	4.3	4.3	4.3	1/°C	Default
5	Power tracking efficiency	0.9	0.9	0.9		Default
6	Power conditioning efficiency	0.88	0.88	0.88		Default
7	Percent standard deviation of load	0	0	0	%	Default
8	Array area	21.02	32.58	16.82	m^2	PV area
9	Area slope	30	30	30	degrees	Roof's slope
10	Array azimuth (South=0)	80	-100	170	degrees	

* Manufacture specification
** Calculated from manufacture specification and physical measurement of the array

TABLE F.11

Summary of Monthly and Annual Electricity Produced and Supplied by the Hybrid PV-T^2 and PV Arrays

Month	Load	Electricity Produced by the PV-T^2 and PV Arrays						Electricity Supplied by the PV-T^2 and PV Arrays		Electricity Sell	Electricity Purchase
		South (PV-T^2)	West (PV-T^2)	West (PV)	East (PV)	North (PV)	Total				
	(kWh)	(kWh)	(kWh)	(kWh)	(kWh)	(kWh)	(kWh)	(kWh)	%	(kWh)	(kWh)
January	448	225	136	225	316	111	1013	88.29	19.7	925	360
February	405	202	131	215	312	125	985	85.85	21.2	899	319
March	448	238	166	268	401	181	1254	106.14	23.7	1148	342
April	434	170	127	210	324	163	995	101.17	23.3	894	332
May	448	188	152	248	393	212	1192	115.74	25.8	1077	332
June	434	164	135	223	356	196	1074	110.33	25.4	964	323
July	448	159	127	212	335	181	1014	109.34	24.4	905	339
August	448	181	139	229	356	184	1089	108.77	24.3	980	339
September	434	172	124	205	312	150	963	95.65	22.1	867	338
October	448	165	111	186	276	121	859	87.22	19.5	772	361
November	434	221	136	224	318	116	1014	87.64	20.2	927	346
December	448	232	137	226	315	105	1016	86.86	19.4	929	361
Year	5275	2317	1620	2668	4014	1847	12466	**1181.01**	22.4	11285	4094

APPENDIX G

INPUT DATA AND RESULTS OF THE ECONOMIC ANALYSIS

Appendix G consists of three sections. Section G.1 presents input data for the annualized life-cycle cost analysis and the results. Section G.2 presents the costs of the base-case house, energy efficiency strategies and the cost of the renewable energy systems that used in the economic analysis. Section G.3 presents economic analysis techniques which includes definitions and equations used in the analysis.

G.1 Input Data for the Annualized Life-Cycle Cost Analysis and the Results

Input data for the annualized life-cycle cost analysis for the individual energy efficiency strategies are presented in Table G.1. The results of the analysis are presented in Table G.3. Input data for the annualized life-cycle cost analysis for Combination A to G are presented in Table G.2. The results of the analysis are presented in Table G.4.

The costs of base-case house and energy efficiency strategies as well as the cost of the renewable energy systems that used in the economic analysis are presented in Table G.5 to G.8. The source of the costs is showed in Table G.9

TABLE G.1

Input Data for the Annualized Life Cycle-Cost Analysis of Individual Energy Efficiency Strategies

	Base-Case House	Insulation on Ceiling	L-W Concrete Block wall	Low-e Windows	Shading Device	High Effi. A/C
Total 1st Yr.Cost =	$63,163	$63,726	$67,527	$65,261	$63,620	$63,912
Invest.Tax Credit =	0	0	0	0	0	0
Life =	25	25	25	25	25	25
Salvage value =	0	0	0	0	0	0
Salvage Year =	25	25	25	25	25	25
Replacement/disposal =	$100.00	$100.00	$100.00	$100.00	$100.00	$100.00
Replace/disposal Yr =	5	5	5	5	5	5
Replacement/disposal =	$100.00	$100.00	$100.00	$100.00	$100.00	$100.00
Replace/disposal Yr =	10	10	10	10	10	10
Replacement/disposal =	$1,302.00	$1,302.00	$1,302.00	$1,302.00	$1,302.00	$1,950.77
Replace/disposal Yr =	15	15	15	15	15	15
Replacement/disposal =	$725.00	$725.00	$725.00	$725.00	$725.00	$725.00
Replace/disposal Yr =	20	20	20	20	20	20
Replacement/disposal =	$100.00	$100.00	$100.00	$100.00	$100.00	$100.00
Replace/disposal Yr =	25	25	25	25	25	25
Discount Rate (id) =	3.00%	3.00%	3.00%	3.00%	3.00%	3.00%
Inflation Rate (j) =	1.80%	1.80%	1.80%	1.80%	1.80%	1.80%
Fuel Inflation Rate (je) =	4.00%	4.00%	4.00%	4.00%	4.00%	4.00%
Mortage Rate (im) =	4.00%	4.00%	4.00%	4.00%	4.00%	4.00%
Annual Electricity Cost	$395.63	$391.58	$359.70	$396.30	$393.53	$381.60
Annual Maintenance =	$50.00	$50.00	$50.00	$50.00	$50.00	$50.00
Annual Insurance=	$50.00	$50.00	$50.00	$50.00	$50.00	$50.00
Depreciation =	7.00%	7.00%	7.00%	7.00%	7.00%	7.00%
Income Tax (%) =	5.00%	5.00%	5.00%	5.00%	5.00%	5.00%
Property Tax (%) =	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
% of system cost =	100%	100%	100%	100%	100%	100%
Salvage Tax =	0%	0%	0%	0%	0%	0%

TABLE G.1 (Continued)

	Base-Case House	Electronic Ballasts	High Effi. Refigerators	PV-T^2	PV	PV-T^2 and PV	Flat-Plate Solar Collector
Total 1st Yr.Cost =	$63,163	$63,345	$63,288	$94,157	$120,303	$135,322	$79,387
Invest.Tax Credit =	0	0	0	0	0	0	0
Life =	25	25	25	25	25	25	25
Salvage value =	0	0	0	0	0	0	0
Salvage Year =	25	25	25	25	25	25	25
Replacement/disposal =	$100.00	$100.00	$100.00	$100.00	$100.00	$100.00	$100.00
Replace/disposal Yr =	5	5	5	5	5	5	5
Replacement/disposal =	$100.00	$100.00	$100.00	$425.00	$325.00	$1,395.00	$200.00
Replace/disposal Yr =	10	10	10	10	10	10	10
Replacement/disposal =	$1,302.00	$1,383.50	$1,302.00	$1,302.00	$1,302.00	$1,302.00	$1,302.00
Replace/disposal Yr =	15	15	15	15	15	15	15
Replacement/disposal =	$725.00	$725.00	$849.52	$885.00	$785.00	$2,020.00	$845.00
Replace/disposal Yr =	20	20	20	20	20	20	20
Replacement/disposal =	$100.00	$100.00	$100.00	$100.00	$100.00	$100.00	$100.00
Replace/disposal Yr =	25	25	25	25	25	25	25
Discount Rate (id) =	3.00%	3.00%	3.00%	3.00%	3.00%	3.00%	3.00%
Inflation Rate (j) =	1.80%	1.80%	1.80%	1.80%	1.80%	1.80%	1.80%
Fuel Inflation Rate (je) =	4.00%	4.00%	4.00%	4.00%	4.00%	4.00%	4.00%
Mortage Rate (im) =	4.00%	4.00%	4.00%	4.00%	4.00%	4.00%	4.00%
Annual Electricity Cost	$395.63	$392.25	$365.33	$224.51	$303.46	$192.37	$289.95
Annual Maintenance =	$50.00	$50.00	$50.00	$100.00	$150.00	$200.00	$100.00
Annual Insurance=	$50.00	$50.00	$50.00	$100.00	$100.00	$100.00	$100.00
Depreciation =	7.00%	7.00%	7.00%	7.00%	7.00%	7.00%	7.00%
Income Tax (%) =	5.00%	5.00%	5.00%	5.00%	5.00%	5.00%	5.00%
Property Tax (%) =	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
% of system cost =	100%	100%	100%	100%	100%	100%	100%
Salvage Tax =	0%	0%	0%	0%	0%	0%	0%

TABLE G.1 (Continued)

	Base-Case House	Combination A	Combination B	Combination C	Combination D	Combination E	Combination F	Combination G
Total 1st Yr.Cost =	$63,163	$69,145	$71,243	$69,602	$71,700	$102,694	$128,839	$143,858
Invest.Tax Credit =	0	0	0	0	0	0	0	0
Life =	25	25	25	25	25	25	25	25
Salvage value =	0	0	0	0	0	500	750	1250
Salvage Year =	25	25	25	25	25	25	25	25
Replacement/disposal =	$100.00	$100.00	$100.00	$100.00	$100.00	$100.00	$100.00	$100.00
Replace/disposal Yr =	5	5	5	5	5	5	5	5
Replacement/disposal =	$100.00	$100.00	$100.00	$100.00	$100.00	$585.00	$870.00	$1,355.00
Replace/disposal Yr =	10	10	10	10	10	10	10	10
Replacement/disposal =	$1,302.00	2132.27	2132.27	2132.27	2132.27	2132.27	2132.27	2132.27
Replace/disposal Yr =	15	15	15	15	15	15	15	15
Replacement/disposal =	$725.00	849.52	849.52	849.52	849.52	1334.52	1619.52	2104.52
Replace/disposal Yr =	20	20	20	20	20	20	20	20
Replacement/disposal =	$100.00	$100.00	$100.00	$100.00	$100.00	$100.00	$100.00	$100.00
Replace/disposal Yr =	25	25	25	25	25	25	25	25
Discount Rate (id) =	3.00%	3.00%	3.00%	3.00%	3.00%	3.00%	3.00%	3.00%
Inflation Rate (j) =	1.80%	1.80%	1.80%	1.80%	1.80%	1.80%	1.80%	1.80%
Fuel Inflation Rate (je) =	4.00%	4.00%	4.00%	4.00%	4.00%	4.00%	4.00%	4.00%
Mortage Rate (im) =	4.00%	4.00%	4.00%	4.00%	4.00%	4.00%	4.00%	4.00%
Annual Electricity Cost	$395.63	311.59	310.24	311.29	309.86	138.80	232.03	108.47
Annual Maintenance =	$50.00	$50.00	$50.00	$50.00	$50.00	$100.00	$150.00	$200.00
Annual Insurance=	$50.00	$50.00	$50.00	$50.00	$50.00	$50.00	$50.00	$50.00
Depreciation =	7.00%	7.00%	7.00%	7.00%	7.00%	7.00%	7.00%	7.00%
Income Tax (%) =	5.00%	5.00%	5.00%	5.00%	5.00%	5.00%	5.00%	5.00%
Property Tax (%) =	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
% of system cost =	100%	100%	100%	100%	100%	100%	100%	100%
Salvage Tax =	0%	0%	0%	0%	0%	0%	0%	0%

TABLE G.3

The Results from the Annualized Life Cycle-Cost Analysis of Individual Energy Efficiency Strategies

	Base-Case House	Insulation on Ceiling	L-W Concrete Block wall	Low-e Windows	Shading Devices	High Effi. A/C
Total 1st Yr.Cost =	$63,163	$63,726	$67,527	$65,261	$63,620	$63,912
Capital & Interest	-$2,932	-$2,958	-$3,134	-$3,029	-$2,953	-$2,967
Salvage value =	$0	$0	$0	$0	$0	$0
Replacement/disposal =	-$4	-$4	-$4	-$4	-$4	-$4
Replacement/disposal =	-$4	-$4	-$4	-$4	-$4	-$4
Replacement/disposal =	-$48	-$48	-$48	-$48	-$48	-$72
Replacement/disposal =	-$25	-$25	-$25	-$25	-$25	-$25
Replacement/disposal =	-$3	-$3	-$3	-$3	-$3	-$3
Operating Costs =	-$496	-$491	-$451	-$497	-$493	-$478
Property tax =	$0	$0	$0	$0	$0	$0
Maintenance =	-$48	-$48	-$48	-$48	-$48	-$48
Insurance =	-$48	-$48	-$48	-$48	-$48	-$48
Interest deduction =	$44	$45	$47	$46	$45	$45
Depreciation deduction =	$50	$50	$53	$52	$50	$51
Total	-$3,513	-$3,533	-$3,664	-$3,608	-$3,531	-$3,553
Annual Elec Cost	$ 395.63	$ 391.58	$ 359.70	$ 396.30	$ 393.53	$ 381.60
Annual Maintenance	$ 50.00	$ 50.00	$ 50.00	$ 50.00	$ 50.00	$ 50.00
Annual Insurance	$ 50.00	$ 50.00	$ 50.00	$ 50.00	$ 50.00	$ 50.00
Annual Mortgage Payment	$4,043.21	$4,079	$4,323	$4,178	$4,072	$4,091
Total Annual Payment	$ 4,538.83	$ 4,570.82	$ 4,782.23	$ 4,673.82	$ 4,565.99	$ 4,572.74
Monthly Elec Cost	$ 32.97	$ 32.63	$ 29.98	$ 33.03	$ 32.79	$ 31.80
Monthly Maintenance Cost	$ 4.17	$ 4.17	$ 4.17	$ 4.17	$ 4.17	$ 4.17
Monthly Insurance Cost	$ 4.17	$ 4.17	$ 4.17	$ 4.17	$ 4.17	$ 4.17
Monthly Mortgage Payment	$ 336.93	$ 339.94	$ 360.21	$ 348.13	$ 339.37	$ 340.93
Total Monthly Payment	$ 378.24	$ 380.90	$ 398.52	$ 389.48	$ 380.50	$ 381.06

TABLE G.3

(Continued)

	Base-Case House	Electronic Ballasts	High Effi. Refigerators	PV-T^2	PV	PV-T^2 and PV	Flat-Plate
Total 1st Yr.Cost =	$63,163	$63,345	$63,288	$94,157	$120,303	$135,322	$79,387
Capital & Interest	-$2,932	-$2,940	-$2,938	-$4,370	-$5,584	-$6,281	-$3,685
Salvage value =	$0	$0	$0	$0	$0	$0	$0
Replacement/disposal =	-$4	-$4	-$4	-$4	-$4	-$4	-$4
Replacement/disposal =	-$4	-$4	-$4	-$17	-$13	-$55	-$8
Replacement/disposal =	-$48	-$51	-$48	-$48	-$48	-$48	-$48
Replacement/disposal =	-$25	-$25	-$30	-$31	-$27	-$70	-$29
Replacement/disposal =	-$3	-$3	-$3	-$3	-$3	-$3	-$3
Operating Costs =	-$496	-$491	-$458	-$281	-$380	-$241	-$363
Property tax =	$0	$0	$0	$0	$0	$0	$0
Maintenance =	-$48	-$48	-$48	-$95	-$143	-$190	-$95
Insurance =	-$48	-$48	-$48	-$95	-$95	-$95	-$95
Interest deduction =	$44	$44	$44	$66	$84	$95	$56
Depreciation deduction =	$50	$50	$50	$75	$95	$107	63 $
Total	-$3,513	-$3,520	-$3,485	-$4,804	-$6,118	-$6,786	-4213
Annual Elec Cost	$ 395.6	$ 392.3	$ 365.3	$ 224.5	$ 303.5	$ 192.4	$ 290.0
Annual Maintenance	$ 50.0	$ 50.0	$ 50.0	$ 100.0	$ 150.0	$ 200.0	$ 100.0
Annual Insurance	$ 50.0	$ 50.0	$ 50.0	$ 100.0	$ 100.0	$ 100.0	$ 100.0
Annual Mortgage Payment	$ 4,043.2	$ 4,054.8	$ 4,051.2	$ 6,027.2	$ 7,700.8	$ 8,662.2	$ 5,081.7
Total Annual Payment	$ 4,538.8	$ 4,547.1	$ 4,516.5	$ 6,451.7	$ 8,254.3	$ 9,154.6	$ 5,571.7
Monthly Elec Cost	$ 33.0	$ 32.7	$ 30.4	$ 18.7	$ 25.3	$ 16.0	$ 24.2
Monthly Maintenance Cost	$ 4.2	$ 4.2	$ 4.2	$ 8.3	$ 12.5	$ 16.7	$ 8.3
Monthly Insurance Cost	$ 4.2	$ 4.2	$ 4.2	$ 8.3	$ 8.3	$ 8.3	$ 8.3
Monthly Mortgage Payment	$ 336.9	$ 337.9	$ 337.6	$ 502.3	$ 641.7	$ 721.9	$ 423.5
Total Monthly Payment	$ 378.2	$ 378.9	$ 376.4	$ 537.6	$ 687.9	$ 762.9	$ 464.3

TABLE G.4

The Results from the Annualized Life Cycle-Cost Analysis of Combinations A to G

	Base-Case House	Combination A	Combination B	Combination C	Combination D	Combination E	Combination F	Combination G
Total 1st Yr.Cost =	$63,163	$69,145	$71,243	$69,602	$71,700	$102,694	$128,839	$143,858
Capital & Interest	-$2,932	-$3,209	-$3,307	-$3,231	-$3,328	-$4,767	-$5,980	-$6,677
Salvage value =	$0	$0	$0	$0	$0	$17	$26	$43
Replacement/disposal =	-$4	-$4	-$4	-$4	-$4	-$4	-$4	-$4
Replacement/disposal =	-$4	-$4	-$4	-$4	-$4	-$23	-$34	-$53
Replacement/disposal =	-$48	-$79	-$79	-$79	-$79	-$79	-$79	-$79
Replacement/disposal =	-$25	-$30	-$30	-$30	-$30	-$47	-$56	-$73
Replacement/disposal =	-$3	-$3	-$3	-$3	-$3	-$3	-$3	-$3
Operating Costs =	-$496	-$390	-$389	-$390	-$388	-$174	-$291	-$136
Property tax =	$0	$0	$0	$0	$0	$0	$0	$0
Maintenance =	-$48	-$48	-$48	-$48	-$48	-$95	-$143	-$190
Insurance =	-$48	-$48	-$48	-$48	-$48	-$48	-$48	-$48
Interest deduction =	$44	$49	$50	$49	$50	$72	$90	$101
Depreciation deduction =	$50	$55	$56	$55	$57	$81	$101	$113
Total	-$3,513	-$3,711	-$3,804	-$3,732	-$3,824	-$5,069	-$6,420	-$7,006
Annual Elec Cost	$395.63	$311.59	$310.24	$311.29	$309.86	$138.80	$232.03	$108.47
Annual Maintenance	$50.00	$50.00	$50.00	$50.00	$50.00	$100.00	$150.00	$200.00
Annual Insurance	$50.00	$50.00	$50.00	$50.00	$50.00	$50.00	$50.00	$50.00
Annual Mortgage Payment	$4,043.21	$4,426.09	$4,560.40	$4,455.34	$4,589.65	$6,573.61	$8,247.24	$9,208.65
Total Annual Payment	$4,538.83	$4,837.67	$4,970.63	$4,866.63	$4,999.51	$6,862.42	$8,679.27	$9,567.13
Monthly Elec Cost	$32.97	$25.97	$25.85	$25.94	$25.82	$11.57	$19.34	$9.04
Monthly Maintenance Cost	$4.17	$4.17	$4.17	$4.17	$4.17	$8.33	$12.50	$16.67
Monthly Insurance Cost	$4.17	$4.17	$4.17	$4.17	$4.17	$4.17	$4.17	$4.17
Monthly Mortgage Payment	$336.93	$368.84	$380.03	$371.28	$382.47	$547.80	$687.27	$767.39
Total Monthly Payment	$378.24	$403.14	$414.22	$405.55	$416.63	$571.87	$723.27	$797.26

G.2 Costs of the Base-Case House's Components and Energy Efficiency Strategies, and the Renewable Energy Systems

TABLE G.5

The Cost of the Existing Components of the Base-Case House

Strategy	Description	Number of Unit	Unit	Material Cost per Unit ($)	Mat. Total Cost ($)	Laber/Construction Cost per Unit ($)	Total Laber Cost ($)	Total Cost ($)	Source
2	Insulation on the 2nd floor's ceiling	69	m^2	$6.84	$472.06	$0.58	$39.68	$512	BTEI, 2004
3	4" brick wall	265.99	m^2	$4.98	$1,323.32	$3.55	$944.28	$2,268	BB, 2004
	Painting	531.99	m^2	$0.75	$398.99	$0.98	$518.69	$918	BB, 2004
	Total							$3,185	
4	Windows and Exterior Doors								BTEI, 2004
	Single pane clear glass	320.51	ft^2	$0.33	$106.41	$1.65	$528.84	$635	
	Wooden frame and Mullion*	19.98	ft^3	$15.20	$303.70	Included in Mat. Cost	-	$304	
	Painting*	365.40	ft^2	$0.16	$58.46	Included in Mat. Cost	-	$58	BB, 2004
	Hinge	32.00	Unit	$2.25	$72.00			$72	
	Handle	23	Unit	$0.88	$20.13			$20	
	Total							$1,090	
5	Shading device (No shading device)	0	m^2	$0.00	$0.00	$0.00	$0.00	$0	
7	Existing Air-conditioning Systems								DIT, 2004
	A/C system-1	1		$625.00	$625.00	$0.00	$0.00	$625	
	A/C system-2	1		$500.00	$500.00	$0.00	$0.00	$500	
	Total						$0.00	$1,125	
8	Magnetic Ballasts	11	piece	$5.00	$55.00	$2.00	$22.00	$77	BTEI, 2004
9	Refrigerators								DIT, 2004
	Refrigerator-1	1	Unit	$475.00	$475.00	$0.00	$0.00	$475	
	Refrigerator-2	1	Unit	$150.00	$150.00	$0.00	$0.00	$150	
	Total						$0.00	$625	

TABLE G.6

The Cost of the Energy Efficiency Strategies and Renewable Energy Systems

Strategy	Description	Number of Unit	Unit	Material Cost per Unit ($)	Mat. Total Cost ($)	Laber/Construction Cost per Unit ($)	Total Laber Cost ($)	Total Cost ($)	Source
2	Insulation on the 2nd floor ceiling	69	m^2	$15.00	$1,035.00	$0.58	$39.68	$1,075	BTEI, 2004
3	4" Light Weight Concrete Block Walls								BTEI, 2004
	4" Light Weight Concrete Blocks	266	m^2	$7.65	$2,034.85	$2.10	$558.59	$2,593	
	Include Light Weight Cement and Light Weight Plastering Cement								
	Form board (Polystyrene)	266	m^2	$16.13	$4,290.48	$1.00	$265.99	$4,556	
	Plastic sheet (Vapor seal)	266	m^2	$1.00	$265.99	$0.50	$133.00	$399	
	Painting	532	m^2	$0.75	$398.99	$0.98	$518.69	$918	
	Total Wall Construction							$7,549	
4	Low-E glass	320.51	ft^2	$2.33	$747.42	$2.48	$793.25	$1,541	Toolbase Service, 2004
	Aluminum frame	211.47	ft	$3.84	$811.25			$811	BTEI, 2004
	Mullion	193.84	ft	$3.84	$743.65			$744	BTEI, 2004
	Hinge	32.00	Unit	$2.25	$72.00			$72	BTEI, 2004
	Handle	23	Unit	$0.88	$20.13			$20	BTEI, 2004
	Total							$3,188	
5	Shading device	40	m^2	$8.93	$357.00	$2.50	$100.00	$457	BB, 2004
7	Air-Conditioning Systems								ConsumerSerch.com, 2004
	A/C system-1	1		$999.39	$999.39	$0.00	$0.00	$999	
	A/C system-2	1		$874.39	$874.39	$0.00	$0.00	$874	
	Total				$1,873.77		$0.00	$1,874	
8	Electronic Ballasts	11	piece	$21.50	$236.50	$2.00	$22.00	$259	Buylighting.com, 2004
9	Refrigerators								ConsumerSerch.com, 2004
	Refrigerator-1	1	Unit	$517.32	$517.32	$0.00	$0.00	$517	
	Refrigerator-2	1	Unit	$232.20	$232.20	$0.00	$0.00	$232	
	Total						$0.00	$750	
10	PV-T^2 System							$30,994	See Table G.7
11	PV system							$57,139	See Table G.7
12	PV-T^2 and PV systems							$72,158	See Table G.7
13	Flat-Plate Solar Collector	230	ft^2	$71	$16,224	Included	$0.00	$16,224	See Table G.8

TABLE G.7

The Cost of the Renewable Energy Systems

Renewable Energy Systems	Description	Cost per Unit ($)	Unit	Number of Unit	Mat. Total Cost ($)	Total Cost ($)	Source
1) PV (on all roof area)	PV Module Cost	$3.04	Wp	11160	$33,926	$33,926	Maycock, P. (2004)
	Power-Related BOS	$1.22	Wp	11160	$13,615	$13,615	
	Includes: DC-to-AC Inverter, Maximum Power Point Tracker and Wiring						
	Area-Related BOS	$0.86	Wp	11160	$9,598	$9,598	
	Includes PV array support structure						
	System Total					**$57,139**	
2) Solar Collector	Not included the PV array Includes absorber plate, heat exchanger piping system, pumps, and preheat tank	$51.09	ft^2	294	$15,019	**$15,019**	See Table G.8
3) PV-T^2	PV Module Cost	$3.04	Wp	3120	$9,485	$9,485	Maycock, P. (2004)
	Power-Related BOS	$1.22	Wp	3120	$3,806	$3,806	
	Includes: DC-to-AC Inverter, Maximum Power Point Tracker and Wiring						
	Area-Related BOS	$0.86	Wp	3120	$2,683	$2,683	
	Includes PV array support structure						
	System Total					$15,974	
	Solar Collector System (from item 2)					$15,019	
	Total					**$30,994**	
4) PV (Not include the PV panels of the PV-T^2 System)	PV Module Cost	$3.04	Wp	8040	$24,442	$24,442	Maycock, P. (2004)
	Power-Related BOS	$1.22	Wp	8040	$9,809	$9,809	
	DC-to-AC Inverter Maximum Power Point Tracker Wiring						
	Area-Related BOS	$0.86	Wp	8040	$6,914	$6,914	
	PV array support structure						
	System Total					**$41,165**	

TABLE G.8

The Cost of a Flat-Plate Solar Collector and Cost Estimation of the Thermal Collection System of the Hybrid PV-T^2 Collector System

No.	Component	Description	Cost	Percentage	Cost/sq.ft
1	2 Solar Collectors	4 x 8 each	$1,350.00	29.9	$21.09
2	Mounting hardware		$300.00	6.6	$4.69
3	Pump		$200.00	4.4	$3.13
4	80 Gallon Storage Tank	Includes heat exchanger	$662.50	14.7	$10.35
5	Others				
	Expansion Tank		$30.00		
	Air Scoop		$13.00		
	Pressure relief valve		$35.00		
	Flow meter		$120.00		
	Temperature gauge		$44.00		
	Differential controller		$110.00		
	Misc. Electric parts		$75.00		
	Misc. Pumbing parts		$75.00		
	Subtotal		$502.00	11.1	$7.84
6	Labor		$1,500.00	33.2	$23.44
	Total		**$4,514.50**	**100**	**$70.54**
From the above data, the following was used to esimate the cost of the thermal collection system of the Hybrid PV-T^2 system.					
	Heat collector plate	Assume 30% of the total collector cost			$6.33
	Items 3 to 6				$44.76
	Total				$51.09

Data of items 1 to 6 was from Innovative Power Systems (www.ips-solar.com/solarheating/cost.htm)
Closed-Loop Solar Domestic Hot Water System for a Typical Minnesota Home

TABLE G.9

The Source of the Estimated Cost Presented in Table G.5 to G.7

No.	Source	Description	Reference
1	Bureau of the Budget, Thailand (BB, 2004)	2004 Thailand Construction Material and Labor Costs	www.bb.go.th Viewed in February, 2004
2	Bureau of Trade and Economic Indices Ministry of Commerce, Thailand (BTEI, 2004)	2004 Construction Material Cost	www.moc.go.th/service_data.htm Viewed in February, 2004
3	Department of Internal Trade Ministry of Commerce, Thailand (DIT, 2004)	Cost of Refrigerators and Air-Conditioning Systems	www.dit.go.th Viewed in February, 2004
4	Toolbase Services (Toolbase Service, 2004)	The Home Building Industry's Technical Information Resource	www.toolbase.org Viewed in February, 2004
5	Buylighting.com (Buylighting.com, 2004)		www.buylighting.com Viewed in February, 2004
6	ComsumerSerch.com (ConsumerSerch.com, 2004)		www.consumerserch.com Viewed in February, 2004
7	Solar Today Magazine, Jan-Feb 2004		Maycock, P. 2004. The State of the PV Market Solar Today, The American Solar Energy Society, Vol. 18, No. 1, January-February 2004

G.3 Economic Analysis Techniques

The annualized life-cycle cost analysis used the following economic analysis techniques, which were obtained from Economic Calculations for ASHRAE handbook (Haberl, 1993).

Definitions of terms:

C_e	=	cost of energy to operate the system for one period
$C_{s,assess}$	=	initial assessed system value
$C_{s,salv}$	=	system salvage value at the end of its useful life in constant dollars
$C_{s,init}$	=	initial system cost
C_y	=	annualized system cost in constant dollars
$D_{k,sl}$ or $D_{k,SD}$	=	amount of depreciation at the end of period k depending on the type of depreciation schedule used, where $D_{k,sl}$ is the straight line depreciation method and $D_{k,SD}$ represents the sum-of-digits depreciation method in constant dollars
F	=	future value of a sum of money
i_d	=	discount rate
i_m	=	market mortgage rate (real rate + general inflation rate)
$i_m P_k$	=	interest charge at the end of period *k*
i'	=	$(i_d - j)/(1 + j)$ = effective discount rate adjusted for energy inflation *j*, sometimes called the real discount rate
i''	=	$(i_d - j_e)/(1 + j_e)$ = effective discount rate adjusted for energy inflation j_e
I	=	annual insurance costs
ITC	=	investment tax credit for energy efficiency improvements, if applicable
j	=	general inflation rate per period

j_e	=	general energy rate per period
k	=	end if period(s) in which replacement(s), repair(s), depreciation, or interest is calculated
M	=	periodic maintenance cost
n	=	number of period(s) under consideration
P	=	a sum of money at the present time, *i.e.*, its present value
P_k	=	outstanding principle of the loan for $C_{s,init}$ at the end of period *k* in current dollars
R_k	=	net replacement(s), repair cost(s), or disposals at the end of period *k* in constant dollars
T_{inc}	=	(state tax rate + federal tax rate) – (state tax rate X federal tax rate) where tax rates are based on the last dollar earned, *i. e.*, the marginal rates
T_{prop}	=	property tax rate
T_{salv}	=	tax rate applicable to salvage value of the system

Single Payment

$$F = P(1+i)^n \tag{1}$$

$$P = F/(1+i)^n = F \times \mathrm{PWF}(i,n) \tag{2}$$

$$\mathrm{PWF}(i,n) = 1/(1+i)^n \tag{3}$$

Accounting for Varying Inflation Rates

$$i' = \frac{1+i_d}{1+j} - 1 = \frac{(i_d - j)}{1+j} \tag{4}$$

$$i'' = \frac{1+i_d}{1+j_e} - 1 = \frac{(i_d - j_e)}{(1+j_e)} \tag{5}$$

$$F = P[1 + i_d / 1 + j]^n = P(1 + i')^n \quad (6)$$

$$P = F / [(1 + i_d)/(1 + j)]^n \quad (7)$$

$$P = F / (1 + i')^n = F \times \mathrm{PWF}(i', n) \quad (8)$$

$$\mathrm{PWF}(i', n) = 1/(1 + i')^n \quad (9)$$

Recovering Capital as a Series of Payments

$$S = P_{ann}\left[1 - (1 + i)^{-n}\right]/i \quad (10)$$

$$P_{ann} = Si / [1 - (1 + i)]^{-n} \quad (11)$$

$$\mathrm{CRF}(i, n) = i / \left[1 - (1 + i)^{-n}\right] = i(1 + i)^n / \left[(1 + i)^n - 1\right] \quad (12)$$

Annualized Costs

C_y = - capital and interest + salvage value – replacements (or disposals) – operating energy – property tax – maintenance – insurance + interest tax deduction + depreciation (for commercial systems) (13)

where

$(\mathrm{CRF}_{s,init}$ - ITC)CRF(i',n)	= capital and interest
$C_{s,salv}$ PWF(i',n)CRF(i',n)(1-T_{salv})	= salvage value
$\sum_{k=1}^{n}\left[R_k \mathrm{PWF}(i', k)\right]\mathrm{CRF}(i', n)(1 - T_{inc})$	= replacements or disposals
C_e[CRF(i',n)/CRF(i'',n)](1-T_{inc})	= operating energy
$C_{s,assess} T_{prop}(1 - T_{inc})$	= property tax
$M(1 - T_{inc})$	= maintenance
$I(1 - T_{inc})$	= insurance

$$T_{inc}\sum_{k=1}^{n}\left[i_m P_{k-1}\mathrm{PWF}(i_d,k)\right]\mathrm{CRF}(i',n) \quad = \text{interest tax deduction}$$

$$T_{inc}\sum_{k=1}^{n}\left[D_k\,\mathrm{PWF}(i_d,k)\right]\mathrm{CRF}(i',n) \quad = \text{depreciation (for commercial systems)}$$

$$P_k = \left(C_{s,init} - \mathrm{ITC}\right)\left[(1+i_m)^{k-1} + \frac{(1+i_m)^{k-1}-1}{(1+i_m)^{-n}-1}\right] \tag{14}$$

$$\sum_{k=1}^{n}\left[i_m P_k/(1+i_d)^k\right] = \left[\frac{\mathrm{CRF}(i_m,n)}{\mathrm{CRF}(\mathrm{i_d},n)} + \frac{1}{(1+i_m)}\frac{i_m - \mathrm{CRF}(i_m,n)}{\mathrm{CRF}(i_d - i_m)/(1+i_m),n}\right]\times\left(C_{s,init} - ITC\right) \tag{15}$$

$$\sum_{k=1}^{n}\left[i_m P_k/(1+i_d)^k\right] = \left[1 + \frac{n}{(1+i_m)}\left[i_m - \mathrm{CRF}(i_m,n)\right]\right]\left(C_{s,init} - \mathrm{ITC}\right) \tag{16}$$

$$D_{k,SL} = \left(C_{s.init} - C_{s,salv}\right)/n \tag{17}$$

$$D_{k,SD} = \left(C_{s,init} - C_{s,salv}\right)\left[2(n-k+1)\right]/n(n+1) \tag{18}$$

VITA

PERSONAL INFORMATION

Name: Sakkara Rasisuttha
Permanent Address: 41/9 Ravadee Rd., Nonthabury, 11000, Thailand
Birthday: February 11, 1971, Bangkok, Thailand
Current Address: Faculty of Architecture, Khon Kaen University
Khon Kaen, 40002, Thailand Phone: 66-043-362-046

EDUCATION

1998-2005 Doctor of Philosophy in Architecture, Texas A&M University.

1996-1998 Master of Architecture, Illinois Institute of Technology.

1988-1993 Bachelor of Architecture, Khon Kaen University, Khon Kaen, Thailand.

WORK EXPERIENCE

2004-Present Lecturer, Faculty of Architecture, Khon Kaen University, Thailand.

1997 Architectural practice, A.L.L Masonry Construction Company, Chicago.

1994-1996 Lecturer, Faculty of Architecture, Khon Kaen University, Thailand, taught architectural design, computer aided design in architecture.

1994-1996 Architect: The Faculty of Agriculture Memorial Building, A lecture building of The Faculty of Humanities and Social Sciences, Khon Kaen University. Thailand. Attached houses, Khon Kaen.

1994-1995 Finalist of 6th and 7th Architect of Siam Association (ASA) Design Competitions.

1993-1994 Application Engineer, Computer Aided Design (CAD) Department, SVOA Public Company Limited, Bangkok, Thailand.